

Muhammad Ikman Ishak
Mohammed Rafiq Abdul Kadir

Biomechanics in Dentistry: Evaluation of Different Surgical Approaches to Treat Atrophic Maxilla Patients

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ISSN 2191-5342

ISBN 978-3-642-32602-8

DOI 10.1007/978-3-642-32603-5

Springer Heidelberg New York Dordrecht London

ISSN 2191-5350 (electronic)

ISBN 978-3-642-32603-5 (eBook)

Library of Congress Control Number: 2012944968

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Preface

The number of edentulous or toothless patients has shown an increase over the last decade. The edentulism phenomenon usually occurs proportional to age or can be due to tooth extraction. Patients can be categorised into two: either fully edentulous or partially edentulous. The latter commonly caused by bone resorption in both jaws, upper (maxilla) and lower jaw (mandible). According to the national surveys conducted by the National Institute of Dental Research (The United States), the rate of edentulism increases at 4 % per 10 years in early adult years and increases to more than 10 % per decade after the age of 70. The number of adult pronounced total edentulism of a single arch was few between the age of 30 and 34 years, however, it increased at the age of 45 to 11 % and then remained constant after 55 years old to approximately 15 % of the adult population. Traditionally, patients with edentulous maxilla and mandible are treated via conventional complete denture to restore esthetics, functions (chewing and speaking) and comfort. However, there were reports of dissatisfactions from denture wearers due to reduced comfort and inefficient oral functions. A new alternative method has thus been introduced to rehabilitate edentulous atrophic bone patients with osseointegrated dental implants.

The osseointegrated dental implant is widely used either to treat complete toothless patients or just for a single restoration. Among the advantages of implant-supported prostheses are preservation of bone and facial esthetics, improve phonetics, occlusion and retention of removable prosthesis as well as increasing the survival rates of prostheses. Anatomical considerations in terms of bone quality and bone quantity play an important role to determine the types of rehabilitation using osseointegrated implants.

The treatment of edentulous maxillary arch through conventional method or total complete denture application is easier to perform compared to similar treatment for the mandibular arch. However, the maxilla is a difficult arch to restore with osseointegrated implants due to its complex morphology and configuration. The limited bone quantity caused by bone resorption especially in the posterior region has resulted in a low implant success rate based on numerous clinical follow-up studies. In comparison, the implant success rate in the maxilla is significantly lower when compared to the implant placed in the mandible. Maxilla

possesses relatively poor bone quality and lower bone density compared to the mandible.

Naturally, the amount of available bone volume in the posterior maxilla is insufficient for implant placement. In order to increase bone volume for dental implant placement in that region, an advanced surgical technique of bone augmentation has been suggested. The augmentation procedure can be performed by harvesting some portion of bone usually from the iliac crest, mandible or other appropriate locations. Onlay grafting, inlay grafting and sinus lifting are some of bone augmentation techniques that can be applied to the affected region. Although this procedure can improve the configuration for potential placement of implant to the affected maxillas, a lower implant success rate has been reported compared to the non-grafted maxillas. Furthermore, the bone augmentation procedure also requires a long treatment time, longer healing time period and a possibility of harvested bone morbidity. Therefore, a new alternative for the treatment of atrophic maxillas was introduced by Brånemark System® in 1988 utilising zygomatic implant to minimise problems or complications caused by the bone augmentation procedure.

Zygomatic implant was initially intended to rehabilitate the maxillectomy patients owing to tumour resection, trauma or congenital defects. However, the function of this implant had been expanded for rehabilitation of edentulous resorbed maxilla patients. It is believed that the anchorage of implant can be achieved at other bone regions that are free from bone regeneration or remodelling. Thus, the selection of zygomatic bone as implant anchorage site is appropriate, evaluated in terms of its anatomical as well as biomechanical aspect. The bone augmentation procedure can be eliminated or slightly reduced via the zygomatic implant approach because of the strength of zygoma arch to retain the implant and prosthesis in position successfully. Four types of surgical approach for zygomatic implant placement that are available in practice are intrasinus (original Brånemark), sinus slot (Stella), extrasinus and extramaxillary approach. In the intrasinus approach, the position of implant body has to be maintained at the maxillary sinus boundaries resulting in a bulky dental prosthesis since the implant head emerges in a more palatal aspect. Extrasinus approach, on the other hand, mainly used to treat patients who have pronounced buccal concavity. In this approach, the zygomatic implant head will be positioned closer to the alveolar crest bone, and therefore, the size of prosthesis could be reduced. Extramaxillary approach is the latest surgical procedure introduced by dental maxillofacial surgeons. This technique is significantly different from the other approaches because the implant body only anchors to the zygomatic arch bone. The emergence of the implant head will be more prosthetically correct compared to intrasinus or extrasinus approach.

There are limited numbers of biomechanical studies on zygomatic implants, many of which have examined the success rate of the implants by clinical follow-up studies. Nearly in all reported clinical studies, the zygomatic implants were demonstrated to have more favourable success rates than standard implants placed in the similar region in maxilla. The cumulative success rate of zygomatic implant

ranges from 98.4 to 100 % during 1–10 years follow-up studies for classic surgical approaches. There are fewer number of finite element studies that have investigated the biomechanical aspects related to the zygomatic implants. Many of them have concentrated on the performance of implant in maxillary defect restoration. More attention is therefore needed to examine the performance of zygomatic implants biomechanically for different surgical approaches to treat severely edentulism cases. In the clinical setting, the most common classic approach is the intrasinus whilst the new approach of extramaxillary was introduced to simplify all other protocols of zygomatic implant surgery.

There are various methods available to measure the stress distribution within peri-implant bone such as photo elastic model studies, strain gauge analysis and two-dimensional (2D) or three-dimensional (3D) finite element analysis (FEA). As FEA is a numerical procedure and requires several assumptions, it is imperative to access the solution accuracy in terms of stress and strain distribution. Moreover, the procedure could also provide accurate representation of complex geometries and simple model modification. It has also been proven as an acceptable method to evaluate dental implant systems accurately over other methods. The use of 3D FEA is a more preferable than 2D technique to evaluate mechanical behaviour of bone and prosthetic components.

To date, despite the reported high success rate of zygomatic implants, failures do occur regardless of the types of surgical approach used. The use of classic surgical approach of intrasinus could result in a higher complication as has been reported in many clinical experiences. Feedback from patients normally regarding discomfort was identified as the main problem on the use of zygomatic implants. The bulky prosthesis may affect dental hygiene and increase the mechanical resistance. Complications of peri-implant soft tissues bleeding and increase in probing depth probably occur due to inappropriate position of zygomatic implant head and abutment. In contrast, implant body mobility and fracture of abutment screw are among complications that have been reported by use of the latest surgical approach, the extramaxillary. Most of the complications are mainly caused by insufficient primary stability achieved by zygomatic implant in supporting the prosthesis. On top of that, the role of alveolar ridge bone support is still questionable since the strength of zygomatic implant anchorage highly depended on zygoma cortical penetration. It is important to highlight that every surgical approach introduced has its own unique characteristic in order to increase the survival rate of zygomatic implants during physiological function. However, to date, there is no specific indication to point out the best approach for implant placement. A key factor for dental implant success or failure is dependent on stress transmission to the surrounding bone. Inappropriate loadings may result in stress concentration at bone region around implant and could lead to bone resorption. It is known that the vertical component plays a major contribution in masticatory loading. Conversely, the role of horizontal component cannot be compromised although its value is minimal especially when angled implant is used. Therefore, there is a necessity to consider different occlusal loading types, vertical and oblique loading in various directions to examine the performance of zygomatic

implants in both approaches. The location of loading application on prosthesis was also another important factor. In short, the statement of current problems can be summarized through the following questions:

- Which surgical approach promotes better implant stability? Complications reported on zygomatic implants are mainly associated with the biomechanical factors of the chosen surgical approach. High quality rehabilitation in terms of function, esthetics and comfort is crucial with regard to a proper surgical approach selection.
- What is the impact of various occlusal loading locations and directions on predicting the success rate of different surgical approaches?

Due to limited availability of data, there is no consensus in terms of the best surgical approach for placement of zygomatic implants. There is a necessity to determine the optimal biomechanical circumstances associated with zygomatic implants placed by different surgical approaches so that they can be admitted as a better alternative treatment modality for severely atrophic maxillae. Follow-up clinical studies and trials alone cannot provide sufficient answers to the problems associated with implant instability. The bio-computational evidence through FEA is also required to explore the load transfer mechanism from zygomatic implant body to the surrounding bone based on stress distribution and implant deformation. Comparative biomechanical study between various surgical approaches can highlight their strengths and weaknesses and provide crucial information for potential improvement.

This text provides an improved understanding of the biomechanics of the treated atrophic maxilla through computational analyses to study the effect of stress distribution and displacement on bones, zygomatic implants and framework under various occlusal and masseter loading. The simulations utilised the meticulous finite element model to represent the clinical settings accurately and act as a prediction tool for the zygomatic implant stability from different surgical approaches for short-term or long-term evaluation.

Malaysia, 2012

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Mohammed Rafiq Abdul Kadir

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Notation

Variable	Explanation
D	Diameter
E	Young's modulus
F	Force
h	Height
L	Length, Load
t	Thickness
w	Width
x, y, z	Cartesian coordinates
ν	Poisson's ratio
μ	Friction coefficient
$\%$	Percentage
σ	Stress
$^{\circ}$	Degree

Chapter 1

Anatomical Considerations

Abstract In this chapter, descriptions towards the anatomy and physiology of human craniofacial are presented. In addition, anatomy and terminologies that are commonly used in dentistry are also described. Considerations regarding on the biomechanics in the field of dentistry especially through the application of osseointegrated dental implant system are also discussed. Further details on the implantation methods, implantation loading, surface topography and material are presented in the following subsections. This chapter provides sufficient information to further enhance the understanding of the next chapters.

Keywords Anatomy • Terminology • Dental implantology

1.1 Anatomy of Human Craniofacial Bones

The adult human skull normally consists of 22 bones. All bones in the skull are joined together by sutures [1], rigid articulations that allow very limited movement [2]. The braincase (neurocranium) has eight bones while fourteen other bones form spalanchnocranium, the bones that support the face. The skull also contains several sinus cavities (frontal, maxillary, ethmoid and sphenoid sinuses), which are air-filled cavities lined with respiratory epithelium and also lines the large airways. The frontal, parietal, temporal, occipital, sphenoid and ethmoid are some of the bones that make up the cranium [1, 3, 4]. The facial bones consist of several portions that change significantly during the first two years after birth. There are about 14 facial bones including two nasal bones, two maxillae, two zygomatic bones, the mandible, two palatine bones, two lacrimal bones, two inferior nasal concha and the vomer as shown in Fig. 1.1 [2, 4].

The human nose is built from a “bridge” that is formed by a pair of nasal bones that meet at the midline. Maxillae, or commonly known as the upper jaw, are a

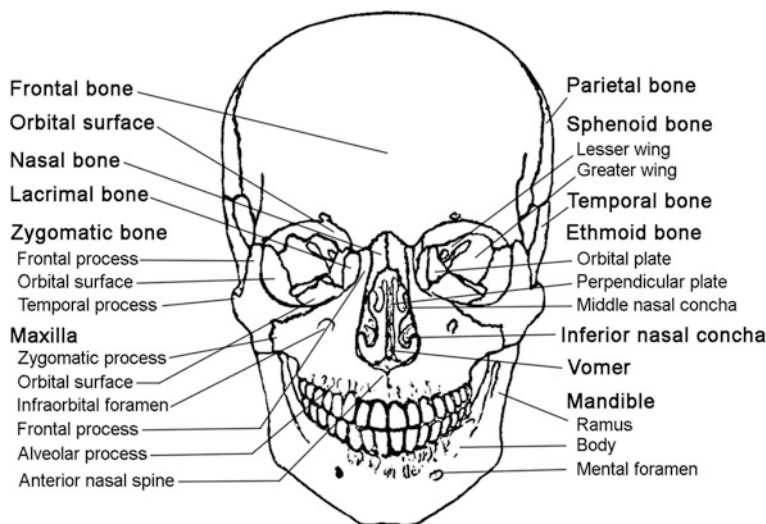


Fig. 1.1 Anterior of human skull

union of two bones at the hard palate. This bone forms part of the orbital floor, part of the nasal cavity lateral walls and floor as well as most of the hard palate [4]. Every bone of the face has articulation with maxilla except the mandible, which is the lower jawbone. The hard palate is formed by the palatine processes of the maxilla and the horizontal plates of the palatine bones. A large maxillary sinus soft tissue is contained in each maxilla and it is unfilled into the nasal cavity. The maxilla also consists of sockets for the upper teeth positioning, called the alveolar process. In addition, there is an opening in the maxilla inferior to the orbit known as infraorbital foramen. It works as a passage of the infraorbital nerve and blood vessels and a branch of the maxillary division of the trigeminal (V) nerve. The other foramen that exists in maxilla is the incisive foramen. It is located in posterior to the incisor teeth. The inferior orbital fissure can be found between the greater wing of the sphenoid and the maxilla [2].

Zygomatic bones or commonly called cheekbones are another paired bone of the skull. It is located at the upper and lateral part of the face and forms the prominence of the cheek, part of the lateral wall and floor of each orbit and parts of the temporal and infratemporal fossa. This zygoma represents four processes, which are the fronto-sphenoidal, orbital, maxillary and temporal process, with four borders. The temporal process of zygoma has an articulation with the zygomatic process of the temporal bone to form the zygomatic arch [4]. Zygoma is free from bone resorption or regeneration compared to other surrounding bones like maxillae [5]. Based on literature studies, zygoma is appropriate to be used as anchorage for implant placement. A long fixture can be installed within the bone starting from alveolar process in maxillae together with ordinary fixtures. The fixture or implant could be used as anchorage for epithesis, prosthesis and obturators [2].

The two lacrimal bones are the smallest bones of the face. These bones located at the posterior and lateral to the nasal bones and they form part of medial wall of the orbits. Palatine bones are paired bones with L-shaped that form the posterior portion of the hard palate, part of the lateral wall and floor of the nasal cavity as well as a small portion of the orbital floors. The vomer is the bone on the floor of the nasal cavity. It is also communicates superiorly with the perpendicular plate of the ethmoid bone and inferiorly with maxillae and palatine bones along the midline [2, 4]. The mandible or also known as lower jawbone is the largest and strongest facial bones. The bone has curvy shape, horizontal part, the body and two vertical parts. The two vertical parts or called as rami or in singular is ramus, has a condylar process, which articulates with mandibular fossa and articular tubercle of the temporal bone to form temporomandibular joint (TMJ). Similar with maxillae, the mandible also has the alveolar process (sockets) for the lower teeth configuration.

1.2 Dental Anatomy

The tooth structure can be divided into two main parts—the crown and the root as illustrated in Fig. 1.2. The crown can be classified into two portions, the anatomical and the clinical crown. The anatomical crown is part of crown that is found in gingival soft tissue whilst the clinical crown is part of crown that is exposed. Teeth consist of several tissue structures like enamel, dentine, cementum and the dental pulp [4]. Enamel is the most outer surface of a tooth and it is the hardest tissue in human body [1]. It acts as a protection to the dentine, which is softer than enamel but harder than bone tissues [6]. It is a living tissue and must be protected during surgical operation. The teeth root is covered by bonelike tissue called the cementum, which is a thin layer tissue with the main function of providing teeth anchorage to the bony wall in periodontium. The periodontium or periodontal ligament provides a gap between the cementum and the alveolar bone. It has a height of approximately 2 mm. The dental pulp contains blood vessels and nerves and it cannot be separated from the dentine either anatomically or functionally [6]. Among functions of the pulp are to form the dentine, provide sensation to the teeth and respond to irritation. The major parts normally involve in most dental practice are teeth, dental arches and periodontal tissue.

Primary teeth in children consist of 20 units and the number increases to 28–32 and will be permanent for adults [1, 4]. The 20 units primary teeth are equally distributed in terms of number for the maxilla and mandible. This is also true for the permanent teeth where a maximum of 16 units are located in the maxilla and mandible respectively. The teeth configuration can be divided into four quadrants, two quadrants for the maxilla and the other two quadrants for the mandible. Each quadrant has two incisors, one cuspid (canine), two bicuspids (premolar) and three molars as shown in Fig. 1.3a and b [3, 4]. Incisors can be classified into central and lateral incisor. The central incisors are located on both sides of the midline of the arch central location. Next to the central incisor is the lateral incisor. Both incisors

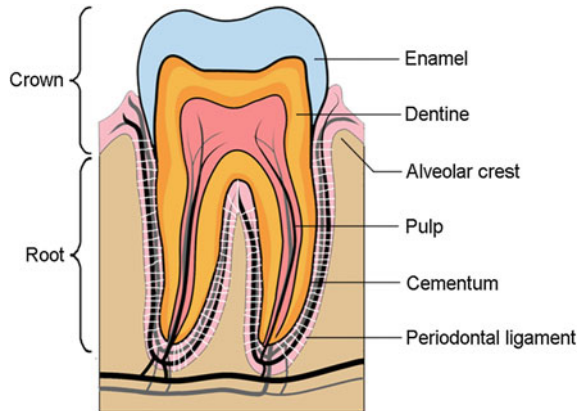


Fig. 1.2 Structure of tooth

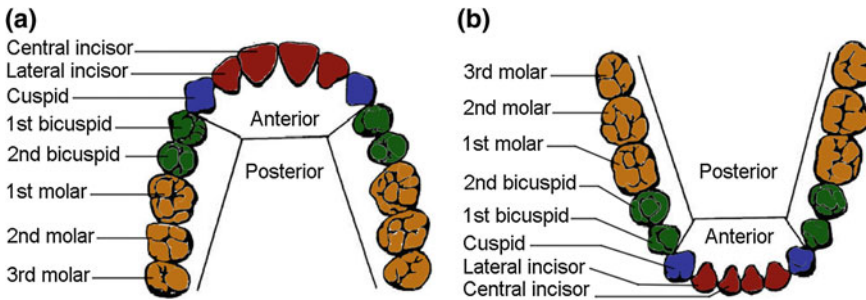


Fig. 1.3 Teeth configuration in the (a) maxilla and (b) mandible

act like scissors during mastication [7]. The teeth located after the incisors are the canine followed by the two premolars (the first and second premolars). The canine has a sharp cusp that effectively tears and shred foods while the premolars have two pointed projections for similar function plus an additional ability to crush food. The most posterior teeth are the three molars; first molar, second molar and third molar. The molars are the strongest and most useful tooth with a main function to grind food into tiny pieces [4, 7].

Several other terminologies are also used in the identification and referencing of teeth structures. The surface of anterior tooth facing the lips is called the labial (or also known as facial) whilst their posterior counterpart facing the cheek is called buccal. The proximal surface nearest to the midline of the arch is known as the mesial and those further away are called distal. Lingual is a terminology that is used to represent the surface of anterior or posterior teeth facing the tongue. Coronal refers to the direction towards the crown of a tooth, as opposed to apical, which refers to the direction towards the tip of the root. Figure 1.4 shows the related terms used commonly in dentistry.

Fig. 1.4 Terms used in dentistry

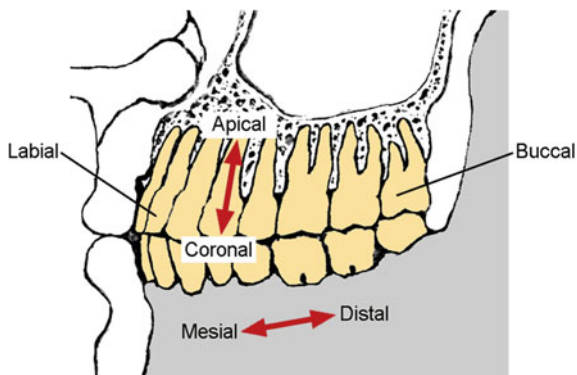
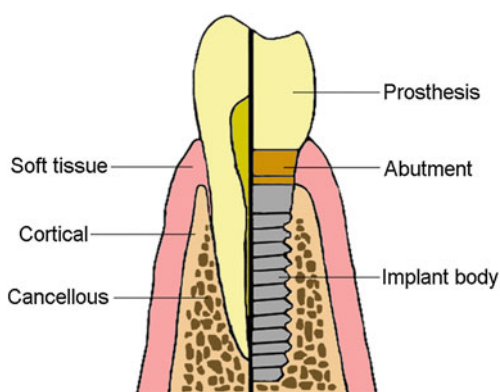


Fig. 1.5 Dental implant



1.3 Dental Implantology

1.3.1 Definition of Dental Implant

According to the Glossary of Prosthodontics, a dental implant can be defined as “a prosthodontic device of alloplastic material implanted into the oral tissues beneath the mucosal and/or periosteal layer, and on/or within the bone to provide retention and support for a fixed or a removable prosthesis” [8]. Basically, a basic dental implant system consists of several parts, which are the implant body, implant abutment and abutment screw. There are various types, shapes and sizes of dental implant commercially available in the market nowadays. The dental implant was introduced to connect the prosthesis to the jaws (maxilla and mandible) such that the occlusal force produced by biting and chewing will be distributed over the surrounding bone [9]. A full structure of dental implant system in bone can be seen in Fig. 1.5. The use of dental implant-supported prosthesis has been accepted as a treatment modality for toothless patients [10]. The tooth replacement can be done

either by partial, complete, fixed or removable dentures relevant to the patient specific cases. The scope of dental implant application has been expanded in craniofacial surgery and also in orthodontics.

1.3.2 Implantation Methods

Transfixation, submucosal, subperiosteal and endosteal implants are implantation methods available in dental implant surgery [8, 11]. The major differences among the methods are dependent on their morphology and method of osseous incorporation [11]. The transfixation implant system is the most traditional method used since 1943 and it has been improved by clinicians through years later. The concept of the system is by the use of a metal or ceramic pin inserted down the root of a tooth and into surrounding bone [8]. The submucosal method, on the other hand, involves the retention of elements under the mucosa membrane. However, it is no longer used due to high bone loss in the posterior maxilla. The subperiosteal implants have a different approach where the implants are placed on the alveolar ridge and linked to the bone by fibrous tissue. This method is not preferable due to the reported low implant success rates. In comparison, the latest method, endosteal implants, is the most acceptable method according to the reported high implant survival rates [11].

1.3.3 Implantation Loading

The term of delay loading is often used as a standard procedure for the treatment of patients using implant in dental practices. The implant body is not subjected to loading for a period of 4–6 months after surgery [12, 13]. This procedure mainly depends on the bone quality, operative side and implant system used. However, a new implantation procedure, immediate loading, has been introduced which eliminates the waiting time of healing and shows an effective outcome with a high success rate reported in numerous clinical-based studies [12, 14, 15]. The immediate loaded implant offers a reduction in cost and time of the implant treatment [12]. It has become a popular treatment option among dental surgeons to treat fully or partially edentulous patients. For the case of edentulous posterior mandible or maxilla, the patients should have at least 11.5 and 5.5 mm of bone height and width, respectively [16]. Besides, the quality of bone measured should be either dense or normal or categorised as Type 1 to Type 3. The number of implants that can be placed ranges from one to three units.

1.3.4 Surface Topography

Dental implants have been currently available in various types of surface roughness characteristics such as machined and oxidized surfaces [14]. The employment of rough surface implant is more suggested as it will increase the implant surface area proportional to the increase of bone-to-implant contact surface [10, 11, 17]. As discussed in several clinical-based studies, the increase of mating surface between implant and bone will allow a higher potential of osseointegration occurrences [11]. The rough surface implant may develop a firmer mechanical link to the surrounding bone tissue compared to implant with machined surface [14]. Furthermore, it also prevents the shear strain action along bone-implant interface during bone remodelling process.

1.3.5 Material

The selection of dental implant material can be made based on two main aspects, chemical perspective and biodynamic activities. Metals, ceramics and polymers are some examples of material categories under chemical point of view whilst biotolerant, bioinert and bioactive materials are grouped under biodynamic activities. Pure titanium and titanium alloy (Ti6Al4V) have commonly become a gold choice for the fabrication of implant body and abutment [11, 18, 19]. Titanium has high biocompatibility, high corrosion resistance and low modulus of elasticity than other metals. Furthermore, it could allow for the bone growth throughout the implant body surface as titanium responses positively to the bone tissues [8, 11].

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Chapter 2

Treatment Options for Severely Atrophic Maxillae

Abstract In this chapter, two main treatment options for severely edentulous atrophic posterior maxillae—bone augmentation procedure and zygomatic implant application—are presented. Poor bone quality and insufficient bone volume due to critical jawbone atrophy in the posterior maxillae are addressed as the main factors contribute to the failure of dental implant system. The rationales behind the introduction of each treatment option are discussed and compared for a better understanding. As this text placed an emphasis on the use of zygomatic implants, a high focus is given to this section covering the specification of zygomatic implants, advantages and disadvantages, indications and contraindications of treatment, types of surgical approach for the implant placement and survival rate of implants. This chapter provides sufficient information on the treatment of patient with severely atrophic posterior maxillae specifically via the use of nongrafting procedure, zygomatic implant. The application of zygomatic implant is gaining popularity over conventional bone augmentation procedure as a treatment modality.

Keywords Bone quality · Bone augmentation · Zygomatic implant · Edentulous jaw classification

2.1 Bone Quality

The success rate of osseointegrated implant in the maxilla especially in the posterior region is significantly lower when compared to the implant success rate in the mandible as witnessed in clinical situations [1–5]. The main factors contribute to the higher implant failure rates in the maxilla are due to poor quality and quantity of bone tissues [1]. Maxillary bone has a lower bone density than mandibular bone especially in the posterior region which makes it unfavourable for osseointegration [5–7]. Furthermore, the anatomy of edentulous maxilla in terms

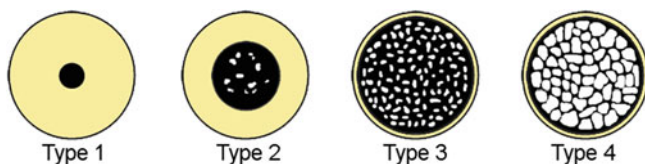


Fig. 2.1 Classification of bone quality

of morphology and configuration has shown limited survival rates for conventional implant placement [2, 6, 8].

Maxillary bone consists of two bone layers, cortical and cancellous bone layer [8, 9]. Cortical bone or also known as compact bone has a higher modulus of elasticity than cancellous bone [8, 10]. There is a higher tendency for better osseointegration process to occur in a higher bone density (cortical) compared to a low bone density (cancellous) [10]. This is likely due to an increase in bone-implant contact that generates a higher strength of anchorage leading to a more stable implant [10, 11]. According to Leckholm and Zarb, the quality of jaw bones can be classified into four main categories as configured in Fig. 2.1 [12].

Type 1 (D1) bone quality is defined as the bone jaws that comprised of homogenous compact bone. While for Type 2 (D2), the bone consists of a dense cancellous bone core surrounded by a 2 mm thick layer of cortical bone. Type 3 (D3) bone consists of a thin layer of cortical bone surrounding a core of dense cancellous bone and Type 4 (D4) bone characterized as a thin layer of cortical bone surrounding a core of low density cancellous bone of poor strength [5, 8, 11]. Generally, the anterior region of maxilla can be classified as Type 3 whilst the posterior region or specifically the molar region is classified as Type 4 [5, 8]. Mandibles are generally more densely corticated than maxillae and both jaws tend to have thinner cortical and increased cancellous porosity towards the posterior [5, 8]. It is important to note that there is a high correlation between implant failure and poor bone density.

2.2 Potential of the Zygoma for Implantation

There was a possibility of placing dental implants in the zygomatic bone as mentioned by Aparicio et al. [13] in 1993. Other than that, the use of zygomatic bone as a support structure for the patients who undergone maxillectomies had been cited by Weischer et al. through a study in 1997 [14]. The measurement of maxilla and zygoma for pre-surgical planning of implant fixation was conducted by Uchida et al. in 2001 using 12 cadavers. The results showed that an implant diameter of 3.75 mm requires a zygoma thickness of at least 5.75 mm [15]. They concluded that an angulation of 43.8° or less increases the risk of perforating the infratemporal fossa or the lateral area of the maxilla. However, an angulation of 50.6° or more increases the risk of perforating the orbital floor [15]. Due to the

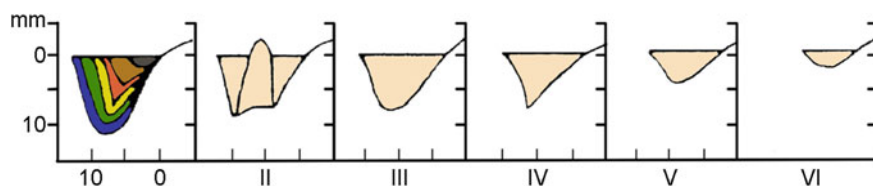


Fig. 2.2 Classification of jaw atrophy in posterior maxilla

curvy and complex shape of the zygoma, implants have to be placed at an appropriate angle with respect to the occlusal plane [16].

Another study done by Nkenke et al. determined the potential of zygomatic bone as a remote site for implant anchorage [17]. Computed tomography images and histomorphometry technique were used to examine 30 human zygomas. The authors revealed that zygoma consists of cancellous bone which is unfavourable for implant placement. Success of implants placed in the zygomatic bone could be achieved by crossing the implant through four cortical layers [17]. In contrast, Kato et al. investigated the internal structure of cadaveric edentulous zygomatic bone using micro-computed tomography and found the presence of wider and thicker cancellous bone at the apical end of the fixture that could be used to promote initial fixation [18].

2.3 Edentulous Jaw Classification

The classification of edentulous jaw is used in dentistry to identify the types of treatment suitable for patients. Jaw atrophy involves a reduction of alveolar height and width as well as bone remodelling that affects the external shape and the internal structure [19]. It occurs in chronic and irreversible fashion due to tooth extraction, trauma, infection, pneumatization of the maxillary sinus and ablative tumour surgery [17]. The pattern of alveolar ridge atrophy, however, is different between maxilla and mandible—maxilla exhibits centripetal resorption while mandible shows centrifugal resorption [20]. There is a higher tendency for bone resorption to occur at the edge of alveolar rather than at the bottom part of the socket after tooth extraction [8, 21]. Based on Tallgren's classic study, more than 2 mm vertical resorption was found in the anterior jawbone between the first year after teeth extraction and insertion of complete dentures. However, the resorption rate of alveolar edge reduced to 0.05 mm/year in the edentulous maxilla and 0.20 mm/year in the edentulous mandible [22].

The resorption of maxilla will move the residual alveolar bone superiorly and medially [8]. In the posterior region of maxilla, critical bone atrophy can result in Class VI thin bone layer with a characteristics of reduced cortical bone thickness, or in a more severe cases a total loss of bone as illustrated in Fig. 2.2 [5]. This is probably due to critical remodelling process which occurs within the cancellous

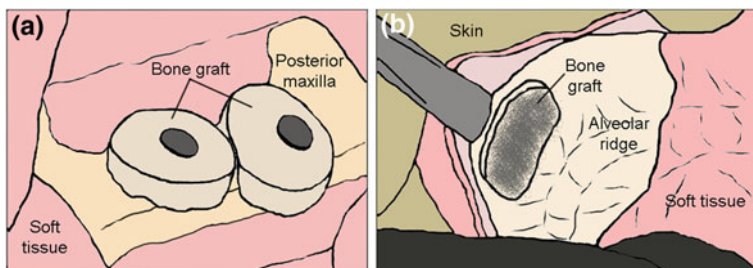


Fig. 2.3 a Onlay bone grafting in posterior maxilla [35] and (b) sinus lifting

bone itself after tooth extraction. The thinning of cortical bone layer reduced the implant anchorage strength, causing a potential failure of osseointegration [8]. The lack of sufficient bone quantity can be solved through various bone augmentation techniques to increase bone volume for dental implant placement in the posterior region of maxilla [2, 23].

2.4 Conventional Surgical Procedure by Using Bone Augmentation

Treatments for edentulous maxilla patients specifically with severe degree of resorption can be performed through several techniques—bone augmentation or grafting; using angled implants in parasinus region; placing implant in the pterygoid apophysis; using short and wide implants; or using zygomatic implants [24, 25]. Bone augmentation has been regarded as the gold standard procedure to treat atrophic maxilla, and the iliac crest is normally used as bone graft [24, 26]. Crestal onlay grafting, inlay grafting (maxillary antrum and nasal floor) or sinus lifting, Le Fort I osteotomy with interpositional grafting and distraction osteogenesis are among augmentation procedures performed to restore the lost bone (Fig. 2.3) [26, 27]. However, this procedure is resource demanding and requires a relatively longer time of treatment and a longer healing period for the patients [26]. In addition, harvesting of bone grafts could cause morbidity or infection of the donor site [17, 26–29].

Based on literature reviews, the survival rate of implant is lower for grafted maxillae compared to non-grafted maxillae especially in the posterior region [27, 28, 30]. It was reported that the use of autogenous drafts lead to a success rate of 87–95 % [27]. Keller et al. conducted a follow-up study of 248 implants placed in grafted maxillae using inlay autogenous bone grafts and reported a success rate of 87 % within a period of 57.1 months [31]. Another study reported by Branemark et al. in 2001 showed 80 % implants with favourable outcome within 2–15 years follow-up using the autogenous onlay bone grafting and simultaneous endosseous

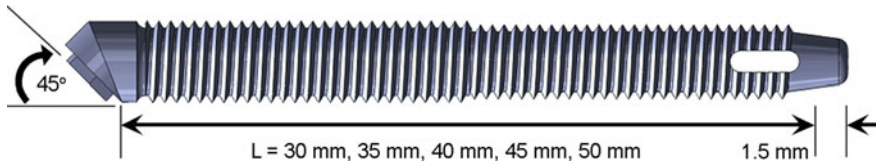


Fig. 2.4 Zygomatic implant specifications

implant placement [32]. Similar results were reported by Lekholm et al. using the same technique of onlay bone grafting with a slightly lower success rate of 75 % [33, 34]. These results were true with the notion that implants placed in native bone has a greater probability of success compared to those implanted in grafted bone [27, 30]. In a comparative study by Widmark et al., a higher success rate was found for implants placed in native bone (96) compared to those using bone graft (82 %) after 1 year follow-up [27]. At 3–5 years follow-up, the success rate of corresponding implants reduced to 87 and 74 %. The nongrafting surgical procedures are therefore preferable for the edentulous atrophic maxilla as the bone augmentation technique resulted in less effective outcomes.

2.5 Advanced Surgical Procedure by Zygomatic Implant Application

Brånemark introduced an alternative system utilising zygomatic implants to overcome complications related to bone augmentation technique [24, 25, 27, 28, 34, 36, 37]. Zygomatic implants were previously utilised to rehabilitate patients who had undergone maxillectomy due to tumour resection, trauma or congenital defect [17, 28, 38]. However, the function of this implant had been extended for rehabilitation of edentulous atrophic maxilla patients. This implant had been introduced to obtain a steady anchorage in zygomatic bone where placement of standard implants would not be possible in the posterior region of maxilla [39].

Zygomatic implant used for the treatment of edentulous atrophic maxillae comes in various dimensions in terms of length, diameter, thread distribution and other features (Fig. 2.4) [40]. Two treatment plans are currently used, either two or more zygomatic implants placed bilaterally without conventional implants support [27, 39], or one zygomatic implant placed bilaterally together with at least two conventional implants placed at the anterior region of maxilla [39, 41–43]. The selection of treatment plan depends on the degree of bone resorption in maxilla. The insertion path of zygomatic implant is usually from the alveolar ridge bone in second premolar or first molar region, going through maxillary sinus or its wall into zygomatic bone [24, 28, 40, 44]. The apical part of implant body will be directed or inserted into the wider and thicker cancellous bone of the zygoma [45].

2.5.1 Advantages and Disadvantages of Zygomatic Implants

The use of zygomatic implants to treat edentulous atrophic maxillae has a lot of advantages over the use of bone graft augmentation incorporation with conventional implants placement in the posterior region. The most prominent advantage is by not using the bone graft itself which is associated with donor site morbidity in the respective region [24, 27, 39, 43, 46]. The total treatment time also reduced as bone grafting procedure requires three to 6 months to heal before the bone can be loaded with traditional dental implants [39, 43, 46, 47]. An additional 6 months are then required to complete the whole process. In the case of immediate implant stabilisation through simultaneous loading and bone grafting, the whole process of prosthetic restoration will therefore take about 6 months to complete. However, this type of treatment is not suitable for patients with sufficient posterior bone volume [27]. The existing patient's maxillary denture can be used as a temporary removable prosthesis prior to the actual prosthesis after soft tissue reline [27, 48]. Treatment using zygomatic implants also requires less hospitalization as the bone grafting technique needs 6 months for bone formation before the actual implant placement. Zygomatic implant approach could also reduce the number of supporting implants at the anterior region due to a steady implant anchorage is achievable in the zygoma, thus, reducing a potential complications [27, 48]. In terms of cost, treatment via zygomatic implant is almost similar to bone grafting.

The main disadvantages of zygomatic implant application are the complexity of implant installation as well as the emergence of implant head in palatal region resulting in an excess bulk of prosthesis causing discomfort. The difficulties to articulate and to perform oral hygiene are some of the common problems caused by the excess protrusion of the implant head. Placement of the zygomatic fixture also requires a well-trained surgeon and restorative dentist has to properly plan the fabrication of a full arch implant-supported prosthesis. Due to the limitation and intricacies of zygoma anatomy, it is difficult to treat patients pronounced concavity of the maxillary lateral wall. Among reported complications associated with zygomatic implants are sinusitis, oroantral fistula formation, periorbital and conjunctiva hematoma or edema, lip lacerations, pain, facial edema, temporary paresthesia, epistaxis, gingival inflammation and orbital injury [27]. Limited intraoperative visibility, complexity of anatomical structures and intricacies of zygoma curve has made this procedure a demanding task [36].

2.5.2 Indications and Contraindications

The role of the zygoma as an implant support structure is indicated in both partial and total maxillary edentulism with a high degree of resorption in the sinus area [49, 50]. Patients with systemic diseases associated with atrophy of the posterior

maxilla are also an indication for the use of zygomatic implants. Balshi and Wolfinger [51], reported a case of congenital ectodermal dysplasia successfully treated with bilateral zygomatic implants in combination with four conventional implants in the anterior region and two pterygoid implants. Peñarrocha et al. [44] published a case of ectodermal dysplasia, where two zygomatic fixtures were placed together with three implants in the anterior maxillary region. An upper complete prosthesis was screwed onto the implants and after 18 months of follow-up, the patient reported significant improvement in oral function and self-esteem.

The reconstruction of maxillary defects following tumour resection or due to maxillectomy is another situation where zygomatic implants have been applied [50]. In this particular case, zygomatic implants are used to anchor an obturator [14] and has been reported to provide increased prosthetic stability, thus improving the life quality of patients. There are several advantages when using zygomatic implants for maxillectomy. Firstly, early detection of postoperative recurrence is easier compared to the one with closed flap. Secondly, when a maxillary prosthesis is supposed to be placed at the midfacial region, zygomatic bone is generally preferred because of its thickness. This could also avoid contracture of the facial soft tissues in the early stages.

Schmidt et al. [52] carried out a retrospective analysis of patients rehabilitated with zygomatic implants following maxillary resection, and presented nine cases of partial or total maxillectomies rehabilitated using 28 zygomatic and 10 conventional implants. Although six zygomatic and three standard implants failed, they concluded that the combination of conventional and zygomatic implants could be used in patients with extensive resection of the maxilla. Landes [53] evaluated the level of satisfaction and indications for zygomatic implants in patients undergoing maxillary resection for various defects. Twelve patients received 28 zygomatic implants and 23 dental implants with a follow-up of 14–53 months. The success rate was 71 % and the quality of life was comparable to those with fixed prostheses over natural dentition.

There are also references to nasomaxillary reconstructions with the aid of zygomatic implants in patients with serious oronasal communications originating from tumour surgery. Bowden et al. [54] presented two cases of nasal reconstruction using implants anchored in the zygoma.

Contraindications of the treatment using zygomatic implants are similar to those applied in the placement of conventional dental implants [13]. Although the intervention in the maxillary sinus cavity could be noted, however, it is not significant to cause local infection. Patients with zygomatic implants may contract an upper respiratory tract infection, which might close to the maxillary ostium, resulting in sinusitis. When this occurs, the sinusitis can become chronic and it is necessary to surgically restore ventilation to the sinuses. There seems to be no increased risk of inflammatory reactions in normal nasal and maxillary mucosa in the regions where titanium implants passed through the mucosa [55].

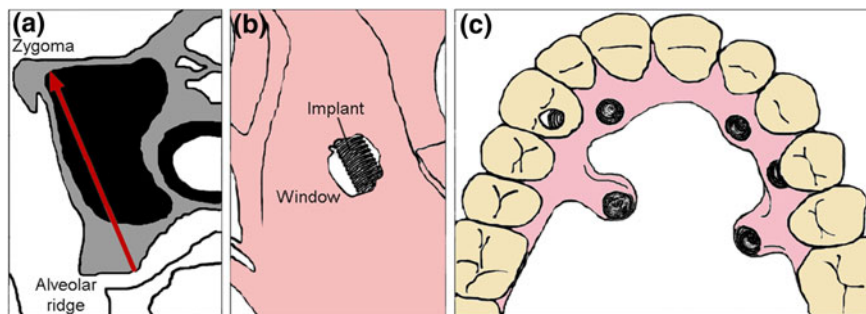


Fig. 2.5 **a** The intrasinus path of zygomatic implant. **b** Lateral window of the maxillary sinus for visual control of implant insertion. **c** Final prosthesis of a patient treated with intrasinus approach. The emergence of implant head is in palatal area

2.5.3 Types of Surgical Approach

There are various types of surgical approach applicable in practice for the placement of zygomatic implants to treat severe edentulous maxilla patients such as intrasinus, sinus slot (Stella), extrasinus and extramaxillary approach since the zygomatic bone has been accepted as a possible implant-anchoring structure. The choice of the surgical technique is determined by the patient's bone anatomy as well as technical skill of the clinician. The original surgical approach of intrasinus was defined by Brånemark System® in 1988, which involved the insertion of a long implant (between 35 and 55 mm) anchored to the zygomatic bone, following an intra-sinus trajectory [56]. The intrasinus has been well-known as a traditional and the most common approach applied to treat atrophic maxillae associated with the use of zygomatic implants posteriorly, with or without additional retentions by conventional dental implants anteriorly.

In the intrasinus approach, the position of zygomatic implant body has to be maintained at the boundaries of the maxillary sinus causing the implant head to emerge in a more palatal aspect resulting in a bulky dental prosthesis (Fig. 2.5a) [27–29, 57]. Patients complaints regarding discomfort should be a cause for concern as this could be due to mechanical resistance of the prosthesis and may affect oral hygiene. Moreover, the penetration of implant body through the maxillary sinus needs to be considered as the condition of the soft tissues will be affected [41]. To perform the surgery via this approach, several protocols have to be followed as described by Brånemark System®. The following descriptions explain the procedures involved for the installation of zygomatic implant via intrasinus approach [58]:

1. The incision of gingival soft tissue is made on the crest or 10 mm palatally to the crest based on Standard Le Fort 1 incision. The purpose of this procedure is to expose the lateral surface of the maxilla up to the zygoma. The location of the infraorbital foramen is identified for anatomic orientation.

2. The alveolar crest including the palatal side is exposed for the drilling purpose.
3. A window with a size of 10×5 mm is made on the lateral wall of the sinus close to the infrazygomatic crest, for observation during implant insertion (Fig. 2.5b). An advanced surgical procedure will eliminate the realization of window opening by the use of surgical drill guide.
4. The sinus mucosa is dissected from the interior sinus wall to ensure that the implant will not pass through the sinus. The sinus mucosa is lifted starting from the floor to the roof of the sinus wall.
5. The zygomatic implant body is planned to be placed as posteriorly as possible. The implant should preferably pass through the sinus close to the incisura point and perforates the cortical layer of the zygomatic bone.
6. The exact point on the alveolar crest is determined to start the drilling sequence. A reactor is placed at the incisura to facilitate the correct 3D orientation of the implant into bone site. The drill guard is used to prevent contact between rotating drill shaft and soft tissue.
7. After the drilling process, the straight depth indicator is utilised to determine the required length of zygomatic implant.
8. To place the zygomatic implant into the prepared bone site, the drilling unit is used with a low speed level. At this stage, the angulation of implant body has to be confirmed until the apical part of implant body reaches the cortical layer of the zygoma.
9. The handle is used to rotate the implant body so that the desired depth and implant head position are achieved.
10. After the implant body has been well-positioned, a cover screw is connected to the head of implant (Fig. 2.5c) to prevent any ingrowth of bone in the internal threads (two-stage procedure).
11. The wound is closed by suturing procedure to minimize post-surgical bleeding.

Stella and Wagner described a variant of the technique, in which the implant is positioned through the sinus via a narrow slot, following the contour of the malar bone and introducing the implant in the zygomatic process [59, 60]. In this way, the need for penetration of the maxillary sinus is avoided, and the implant will emerge over the alveolar crest at the first molar level, with a more vertical angulation. This technique is better than the intrasinus because the flap is more conservative, causing less trauma and improving the postoperative course. The outcome of prosthesis is also improved aesthetically and functionally without hybrid rehabilitation [34].

The surgical procedure is initially started by a crestal incision from one maxillary tuberosity to another in the opposite side. At the end of incision, 1 cm additional vertical releasing incision is made bilaterally [60]. Similar with intrasinus approach, the traditional Le Fort 1 standard can be performed to expose the base of piriform rim, up to the inferior aspect of infraorbital nerves, and around the inferior half of zygoma body bilaterally. The flap is considerably simpler

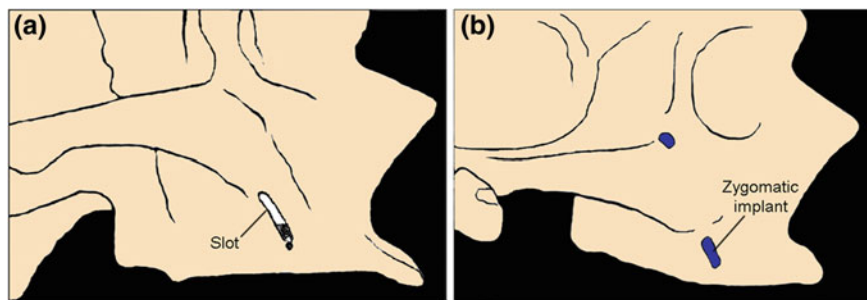


Fig. 2.6 **a** Preparation of sinus slot in bone. **b** Complete operative site preparation together with the placement of zygomatic implant

compared to the traditional approach, which covers the level of infraorbital rim and the superior aspect of the zygomatic arch [60]. Two burr holes are created; one at the superior aspect of the height of zygomatic buttress contour and the second hole 5 mm above the crest of alveolar bone. Zygomatic implant depth gauge is used to prepare the holes and used to simulate the angulation of implant placement during drilling process. Both holes are then connected by drilling a slot from the buttress wall to the floor of maxillary sinus (Fig. 2.6a) [60]. The slot preparation will not affect the sinus membrane.

The 2.9 mm zygomatic implant twist drill is used and placed over the alveolar crest bone. It is directed through the center of sinus slot towards the junction of orbital rim and zygomatic arch (Fig. 2.6b). The drilling process is repeated with a 3.5 mm pilot and twist drill to widen the inferior aspect. The depth gauge is used again to reconfirm the preparation of implant depth. In order to ensure a proper angulation of the implant platform, a hexagonal machine screwdriver (DIA 186) is placed on the implant mount screw. It should be allowed to rotate in proper position when the implant is turned with the hand wrench [60]. Peñarrocha et al. [61] detailed the use of this technique, presented five clinical cases and discussed the advantages of the Stella and Wagner system over the original Brånemark technique. Boyes-Varley et al. disagree with the sinus slot technique since perforation of the posterior antral wall is possible due to lack of visibility [62].

Extrasinus or also known as exteriorized approach, on the other hand, is mainly used to treat patients pronounced with buccal concavities at the maxillary sinus lateral wall [28]. It is impossible to install the fixtures using the intrasinus approach particularly for this type of patients. By using this approach, the zygomatic implant head could be positioned closer to the alveolar crest bone, and therefore, the size of prosthesis could be reduced (Fig. 2.7). One of the most important inclusion criteria to perform this approach is the presence of buccal concavity at the maxillary sinus wall that precluded intrasinus placement with the implant head emergence within a distance of 10 mm medial from the top of the alveolar crest [28]. The general and local health of patients that prevent the use of general anesthesia and intraoral surgery are the exclusion criteria for this approach.

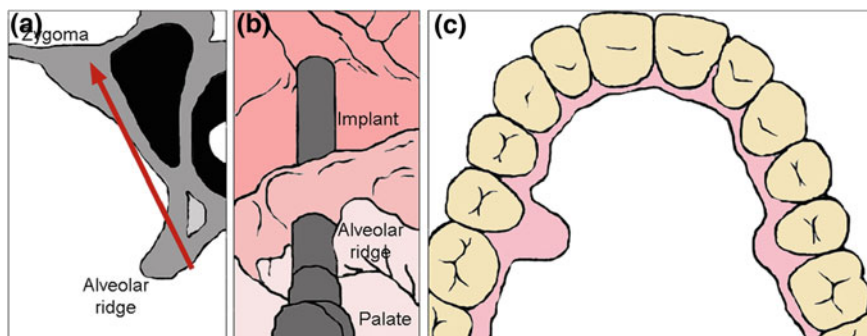


Fig. 2.7 **a** The extrasinus path of zygomatic implant. **b** The zygomatic implant pass through the extreme buccal concavity from the alveolar crest to the zygoma. **c** Final prosthesis of a patient treated with extrasinus approach. The emergence of implant head is slightly in the palatal area

Most of the surgical procedures involved are similar to that of intrasinus approach, except for the opening window creation to the maxillary sinus wall and sinus membrane integrity consideration. Moreover, the path of implant insertion is also different, in which the implant body anchors in an extrasinus path, and it should preferably engage the lateral wall of maxillary sinus before penetrating the zygoma arch [28]. The implant body could be completely or partially outside the sinus cavity. Aparicio et al. reported a mean distance of 3.8 mm from the zygomatic implant head to the central part of alveolar crest using extrasinus approach, which was less than 11.2 mm, recorded by the control group through intrasinus approach. This could prove that the approach results in less bulky of prosthesis construction that beneficial for cleaning purpose and providing better comfort to the patients.

Extramaxillary is the latest surgical technique for the treatment of edentulous atrophic maxillae. It was introduced to simplify the earlier surgical approaches of zygomatic fixtures and to improve the quality of rehabilitation in terms of aesthetics, function and comfort for patients. This technique is significantly different to the other approaches because only the implant body anchored in the zygomatic arch (Figs. 2.8a and 2.8b) [41]. The crestal part of implant body only accommodates at the maxilla externally using a zygomatic implant with different thread distribution and covered with soft tissue. Hence, the emergence of the implant head will be more prosthetically correct in comparison to the other classical approaches (Fig. 2.8c) [41]. This approach could also avoid the introduction of foreign object into sinus cavity that could initiate sinusitis to patients [39]. In real clinical situation, surgeons will start the surgery by performing mucoperiosteal incision on the maxillary arch from molar to molar to allow flap reflection. The incision is also made on the zygomatic process by having two vertical-releasing to expose the inferior edge of the zygomatic bone, similar with other approaches. A distance of 3 mm from the vertical edge of the zygoma is kept in order to place the extramaxillary implant within bone as posteriorly as possible. This is done to

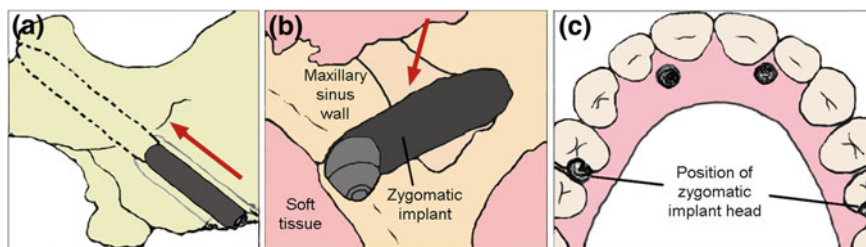


Fig. 2.8 **a** The extramaxillary path of zygomatic implant. **b** The zygomatic implant accommodates the maxillary and anchors in the zygoma. Arrow marks the intact maxillary sinus membrane. **c** Final prosthesis of a patient treated with extramaxillary approach. The emergence of implant head in the posterior region is slightly in the maxillary arch

reduce the cantilever effects of the fixed implant-supported prosthesis as well as to allow for the placement of additional zygomatic implants if needed in future. A round bur is used to create a path from the maxillary bone to the zygoma inferior edge, followed by the drilling process. During this process, surgeons will feel the preparation of the external cortical bone by placing the thumb at that area. In addition, the soft tissues need to be protected by using retractor and drilling guard. Any possibility of damage of the infraorbital nerve can be avoided since a direct observation of anatomical structures is achieved. Moreover, the penetration of maxillary sinus medial wall and its sinus membrane could be avoided through this approach in most patients' cases. However, in particular cases, the sinus mucosa can still be perforated by the implant body because the position of the soft tissue is in the pathway of drill direction [41].

In the classical surgical approaches either intrasinus, sinus slot or extrasinus, the zygomatic implant body is installed to a depth of 18.2 in the zygomatic bone whilst 6.2 mm in the posterior region of maxilla [42]. However, according to some authors, the implant can also be fixed 8–10 mm in the zygomatic bone [40]. The head of implant body was designed in specific angles such as 25, 45 and 55° respected to the occlusal plane to make it easier to establish a common path of implant insertion. Generally, the 45° implant head is mostly utilised since there is no restriction by the sinus or alveolar bone.

2.5.4 Survival Rate of Zygomatic Implants

It can be concluded that zygomatic implants recorded a high survival rate which is about 98.4–100 % based on 20 clinical follow-up studies [24]. Most of the studies have involved the use of conventional dental implants that placed in the anterior maxilla to support the prosthesis. Figures 2.9 and 2.10 depict the failure rates of the zygomatic and conventional dental implants, respectively, reported by several authors from 2001–2008.

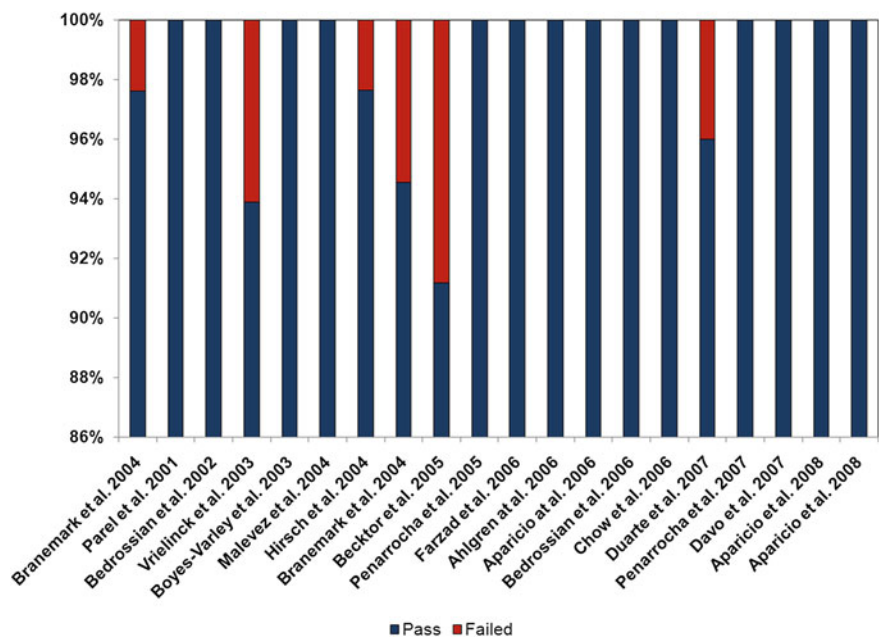


Fig. 2.9 Zygomatic implant failure rates based on 20 clinical follow-up studies

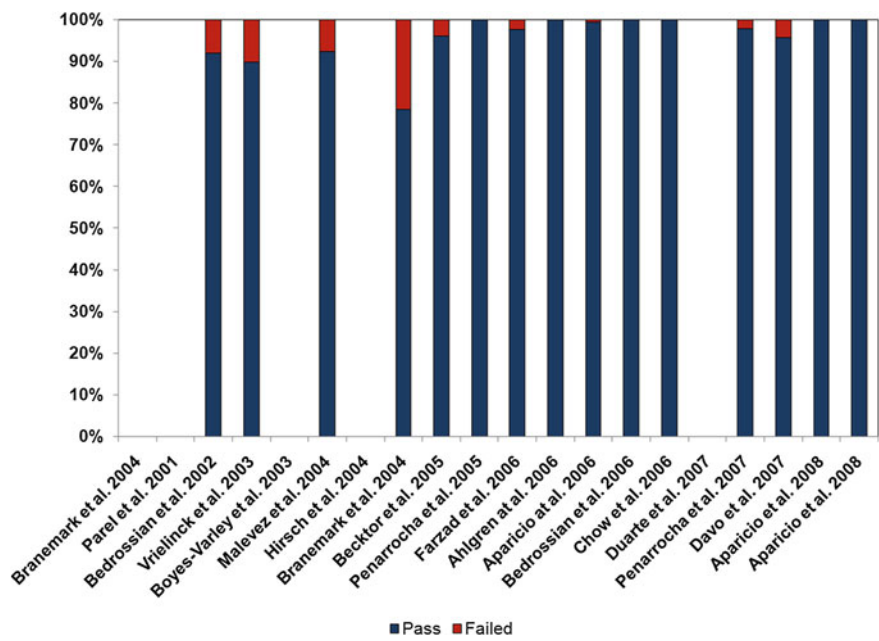


Fig. 2.10 Conventional dental implant failure rates based on 20 clinical follow-up studies

There were more than 1,000 zygomatic and conventional implants placed in more than 500 patients with a total of follow-up study of 6 months to 12 years. The primary inclusion criteria for this survey are the placement of zygomatic implants for the treatment of severely atrophic posterior maxillae and also maxillary defects. The zygomatic implants were placed through the classical intrasinus approach for the treatment of atrophic maxillae. According to Aparicio et al. the cumulative failure rates of zygomatic implants and conventional dental implants were 1.6 and 5.2 %, respectively. Most of the treatments involved the use of one zygomatic implant installed bilaterally in conjunction with conventional dental implants support in the premaxillary region. There was only one case of two zygomatic implants placed bilaterally without additional retentions by conventional implants. Out of 48 zygomatic implants, two implants had failed with a follow-up of 30 months. Besides, five studies were conducted under immediate loading function. According to Block et al. there was no significant effects on the complications or implant failure rates caused by smoking [27]. This was supported by Ahlgren et al., who reported 100 % success rate of zygomatic implants achieved under a follow-up study of 11–49 months [63]. Another study by Aparicio et al. in 2006 found the similar result when 69 patients (27 smoked) treated with 131 zygomatic implants within a period of 6 months to 5 years follow-up [27].

Although the route of zygomatic fixtures has concerned the intrasinus trajectory, it did not seem to provoke any biological or soft tissue complications. However, a few studies have had highlighted this issue. In a study of 1–6 year's follow-up, Becktor et al. investigated 31 zygomatic implants placed in 16 patients. Three zygomatic implants failed (9.7 %) and had to be removed due to recurrent sinusitis in spite of successful osseointegration. The causative factors of sinusitis could be because of a communication created from oral cavity into maxillary sinus or mobility of the implant during function, which caused by the lack of osseointegration at the marginal bone around the neck of implant. Some other studies also reported on similar complication of sinusitis with 2.3–13.6 % occurrence [24]. Through a study in 2006, Becktor had summarised that the sinusitis occurrence is not related to the stability of implants and prosthesis [64]. Other than that, intra-oral infections were among complications seemed to occur for about 3.8–31.8 %. One study reported that out of 20 zygomatic implants, nine of them failed as observed by bleeding of periimplant soft tissue and increasing of probing depth. These problems could be caused by inappropriate position of zygomatic implant body and abutment due to the chosen surgical approach. In addition, the design of prosthesis itself also plays an essential role for successful clinical outcomes [24].

The performance of zygomatic implants via the extrasinus approach also achieves an excellent survival rate. According to Aparicio et al. who has first experienced with the technique, 36 zygomatic fixtures were used to treat 20 patients pronounced with buccal concavities within a period of 12 months follow-up. The finding showed that none of the implants failed. It was also supported by no pain, discomfort or complications recorded up to 18 months follow-up. The convincing and encouraging outcomes showed by this approach have made it as an

appropriate treatment option to place the zygomatic implants in patients pronounced with buccal concavities in the posterior maxilla.

Malo et al. reported 98.5 and 100 % cumulative survival rates for implants (conventional and zygomatic) and prosthetics, respectively in 1 year period follow-up study [17]. The study investigated the application of the extramaxillary approach in the treatment of atrophic maxillae using a new zygomatic implant design in immediate function. The results found that one zygomatic implant failure was observed caused by implant mobility where there was disconnection between implant and prosthesis. The occurrence of sinus soft tissue infection was also detected, as the patients had experienced in diagnosis of maxillary sinusitis prior to the surgery that could be associated with the rupture of sinus membrane during surgical phase.

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Chapter 3

Biomechanical Considerations

Abstract In this chapter, the theoretical background of biomechanics in the field of dentistry especially through the application of osseointegrated dental implants is presented. This includes the description of force distribution by natural teeth and also dental prostheses for patients treated with osseointegrated implants. Reports from several past clinical-based findings on force transmission in dental implant system and also the application of finite element methods in predicting the performance of dental implant complex are also discussed. This chapter also put an emphasis on the explanation of biomechanical aspects in different implant-supported restorations (fixed implant-retained prosthesis and implant-retained overdenture) and also in the application of zygomatic implants for the treatment of patients with severely atrophic posterior maxillae.

Keywords Force distribution • Implant-bone interface • Implant-supported restoration • Finite element analysis

3.1 Force Distribution by Natural Teeth

High survival rate of dental implants in a long-term performance can be guaranteed by a good bone-to-implant connection. The main factor contributes to the failure of dental implant system is the implant overloading as been reported from many clinical cases. In order to avoid the overloading on implant body, the mechanical stresses generated from the masticatory forces action need to be transferred to the bone, in which could leave unfavourable effects on the surrounding tissues. Therefore, it is very important to well understand the behaviour of the forces acting on implants, the forces transmission to surrounding bone and the response of interfacial tissues in ensuring the performance of dental implants.

The periodontal ligament plays a very important role in the biomechanics of natural teeth, in which lacks by an osseointegrated implant. The action of masticatory force from chewing or biting demonstrates micromovements in the horizontal and vertical directions as a result of the periodontal membrane resiliency [1, 2]. The masticatory force is resolved into vertical and horizontal components as it is applied to the natural teeth or tooth-supported restoration. The movement is greater in the horizontal direction as compared to the vertical direction. As mentioned by Weinberg, the micromovement of the periodontal ligament allows the distribution of force along the root surfaces around the center of rotation in the apical third [1, 3]. The maximum value of bite force by adults is generated in the molar region [4] and it can be influenced by age, sex, degree of edentulism and bite location [5]. Individuals with the age range from 75 years and above have 40 % lower bite force than those of 35–44 years [6].

3.2 Biomechanics of Implant-Bone Interface

3.2.1 Occlusal Forces in Patients Treated with Osseointegrated Implants

Each individual has different bite forces configuration in terms of magnitude or location throughout the dental arch. Occlusal forces have high load magnitudes with high frequency but short duration. For normal people with natural dentition, the bite forces are five to six times higher than complete denture wearers [7, 8]. The vertical component of bite forces ranges from 100 to 2400 N for people without implants or dentures [9]. The average value of bite force by patients treated with implants is reported to be 50 N and the maximum value to be 150 N [10].

The axial force component tends to increase distally in the mouth due to the biomechanics of jaw elevator muscle as well as the lever system of the mandible [4, 11, 8]. It is reported that the force exerts in the molar region exceed four times higher than it does in the incisor region. This can be described by the concept of 3-Lever class where a higher force is required to lift the weight as the force moves nearer to the fulcrum [1, 12, 4, 11]. In human mastication, the temporomandibular joint will act as a fulcrum and the forces in the posterior region have a higher magnitude than in the anterior region [12]. Among factors that influence the value of axial force component are locations of force application, nature of food, chewing configuration, age, gender as well as mental condition of patients [1].

3.2.2 Force Transmission from Implants to Bone

When the masticatory load is applied to the implant-supported prosthetic restoration, the prosthesis crown being the first part to get affected before the force

reaching to the bone-implant interface via the implant body [8]. The deformation of dental implant can be verified by the deformation of alveolar bone and it is about 10–100 times less than the deformation of natural tooth [1]. There are several factors majorly influence loading on dental implants such as:

1. Magnitudes, locations and directions of applied occlusal forces on the prosthesis [2, 8, 13].
2. Type, geometry and rigidity of the prosthesis.
3. The nature of connection between the restoration and the implants [13].
4. The number, location, angulations, geometry, length and diameter of the implants [2, 8, 13].
5. The mechanical properties of the implants and the prosthesis.
6. The stiffness of the implant interface [2].
7. Condition of the opposing arch (natural dentition or prosthetic restoration).
8. Functional jaw and skull deformation.
9. Quality and quantity of the available bone [2, 14, 8].
10. Type of food [8].

The shape of occlusal surface contact or the intercuspal position of prostheses and natural teeth gives a significant influence on force transmission from implants to bone [2]. As mentioned earlier, the force is resolved into two main components, which are the vertical and horizontal force components, and this process is referred as vector resolution [5, 15]. The vertical component acts only in the occlusoapical direction, while the horizontal component operates into two directions, the buccolingual and mesio-distal directions. According to Brunski, the vertical forces give more significant effects on dental implant stability compared to horizontal forces as the horizontal forces are up to one-tenth of vertical forces magnitudes [16]. However, if the occlusal force exerted on the implant restoration resulting in a high magnitude of horizontal component (faciolingual axis), the implant is exposed to a high risk for fatigue failure [5].

The types of force can be categorised as tensile, compressive or shear. Tensile force exerts on the implant body will tend to pull it apart while the action of compressive force cause it to be pushed against each other. The implant body has a higher tendency to slide if the shear force is applied. Among the forces, the shear force is the most unfavourable since it can highly cause destructive to implants and bone. In comparison, the compressive force typically should be dominant in implant prosthetic occlusion [5].

Once the force exerts on the occlusal surface of prosthesis the mechanical stresses will be generated through the implant and restoration specifically at load-bearing system. The stresses are also produced within the surrounding bone tissues with the same magnitude but in the opposite direction. Most of stresses concentrate at the bone-implant interface with a higher value found in the crestal region rather than in the apical part. The magnitude of stress is highly dependent on the force magnitude and cross-sectional area over which the force is dissipated.

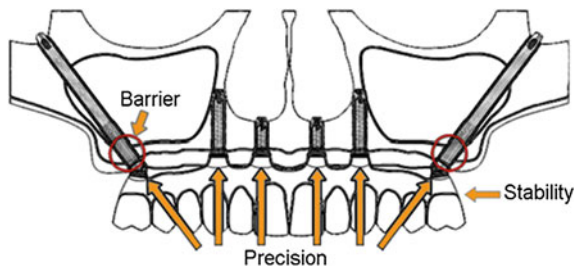
3.3 Biomechanics of Implant-Supported Restorations

The rehabilitation of patients with highly resorbed edentulous maxilla with osseointegrated dental implants is identified to be difficult owing to poor bone quality and quantity. It is vitally important to appropriately plan and consider the behaviour of natural occlusal forces to achieve optimum biomechanical circumstances, especially for the implant-supported restorations [17].

Various types of implant-supported restorations are commercially available such as fixed implant-retained prosthesis and implant-retained overdenture. For the case of edentulous atrophic maxillae it was reported that the implant-retained overdenture is the most suitable treatment restoration [1]. This is due to the application of force on an overdenture resulted in lower compressive loads, but higher bending moments on implants than the fixed restorations [8]. While the fixed restoration has a higher potential to deal with mechanical and biological problems according to Jemt [18] as well as Zitzmann and Marinello [19]. An *in vitro* study conducted by Jager et al. showed that the strain values recorded within overdenture were dependent on the types of connector used [1]. The types of connector that can be used to secure overdenture to implants are either using bar types or individual attachments like ball anchors, rigid telescopic copings, non-rigid telescopic copings and magnet attachments [20, 21]. For the types of bar, they can be categorised as Dolder joint bars (egg-shaped), round bars and rigid bars (U-shaped) [1, 22]. There are also bars with or without distal or mesial extensions for specific patient cases.

In many cases, it is believed that the fixed implant-retained prostheses get more acceptances and satisfactions from patients. This is proved with a higher clinical success rate achieved by fixed restoration as compared to overdentures [22]. The lower success rates of overdenture could be due to lack of biomechanical aspects of implants and prostheses. It was suggested that the implants are installed in the posterior region or edentulous arch so that the force can be widely distributed, which is not concentrated on the most distal implant. The acceptance and satisfaction of patients on superstructure types could be different based on patient's perception, treatment psychological responses as well as assessment of the treatment result. According to Zitzmann and Marinello [23], the outcome of their study on patient's assessment demonstrated that there was no significant difference between both restorations. Both restorations exhibited improvements in comfort and retention, functions, aesthetics, speech and self-esteem [23]. This situation contradicts several thoughts that the fixed restoration offers better outcomes in terms of functions and patients satisfaction. An *in vivo* study conducted by Mericske-Stern et al. [22] reported that the force transmission from the prosthesis to the implant body was found similar between fixed implant-retained prosthesis and implant-retained overdenture. The study also indicated that the presence of bar design in an overdenture did not give significant effects on the force patterns.

Fig. 3.1 Biomechanical considerations in zygomatic implant application



3.4 Biomechanical Considerations of Zygomatic Implant Application

Zygomatic implants have a higher tendency to deform under the horizontal or lateral loading in comparison to conventional dental implants. The main factors contribute to the deformation of implants are the increase in implant length (30.0 mm to 52.5 mm) as well as the limited bone support in the alveolar bone [24]. The effects of occlusal force from biting and chewing action may cause the generation of bending moment that acting on the zygomatic implant body. The bending moment effect is adverse as it can put at risk the long-term of implant stability. There are several ways to stabilise the zygomatic implants in supporting the prosthesis such as by cross-arch stabilisation, decreased buccal lever arms, decreased cantilevers, balanced occlusion and decreased cuspal inclination.

There are various parameters which contribute to the stability of zygomatic implant relating to the prosthesis design, which are stability, precision and barrier, as can be seen in Fig. 3.1. Prosthetic design stability can be defined as the potential of bridge framework to sustain the implant position by having minimum implant movement or displacement especially under horizontal loading action. The term of prosthetic design precision refers to the strength of connecting screw joints to secure the position of prosthesis and abutment. Therefore, the prosthetic designs should have an effort to incorporate sufficient rigidity and precision in the restoration. Besides, the design criteria of prosthetic restoration have also to decrease the bending moments as the bending moments may cause the deformation of implant body. The implant deformation should be avoided as it will lead to the failure of implants or screw loosening [24].

The use of tilted or angled implants particularly in the posterior region to treat atrophic maxilla patients showed an increase with short and medium term clinical success [25, 26]. Several clinical follow-up studies stated that the survival rates of angled implants placed in posterior maxilla were from 92.8 to 98.8 % in combination with the use of axial implants under delay loading [26, 27]. The application of zygomatic implant has a similar concept with the use of distal implant in particular inclination to restore and rehabilitate the prosthetic functions. The rationale behind the inclination of distal implant is based on biomechanical

viewpoint, where the cantilever length can be reduced and the polygonal area for prosthetic support will be increased.

Other than that, longer implants can be used to increase the surface area contact with bone tissues for a better osseointegration. The anchorage of implant to bone with more than one cortical plate will increase the initial implant stability [26, 28]. There was an experimental study done by Geremia et al. and the results showed that a better general biomechanical behaviour of tilted distal implant was observed when compared with straight implant for the same cantilever extension [25]. The installation of posterior implant in distal direction parallel to the anterior sinus wall is required to avoid the penetration of implant body through sinus mucosa and to provide better implant retentions. The zygoma was claimed to absorb most of the posterior loads while the conventional dental implants in the premaxillary region responsible to the anterior loads [26]. This could therefore reduce the adverse masticatory loading and cantilever effects on the zygomatic implant body.

3.4.1 Previous Biomechanical Study of Zygomatic Implants

Ujigawa et al. conducted a study on zygomatic implants to measure the stress distribution within craniofacial structures and superstructure itself through 3D finite element method [29]. The study had compared the configuration of zygomatic implants with and without connected implants to support the superstructure. The outcome of study showed that most of stresses were sustained by the zygomatic bone, at the middle part of the implant body and at the connection of implant-abutment for the case without connected implants. For the case with connected implants, there were less stresses concentrated within the alveolar bone around the head of zygomatic implant. The occlusal loading was primarily sustained by the zygoma and the stresses were dispersed into temporal and frontal processes.

The evaluation of zygomatic implants in the unilateral maxillary defect restoration was done by Wu et al. in 2008. The aim of the study was to investigate the biomechanical criteria and functional design of the unilateral maxillary reconstruction method using the microsurgery bone graft and zygomatic implant [30]. The results found that the highest stress magnitude was generated at the neck of implant on the zygomatic bone whilst the rest of peri-implant bone was observed to sustain lower stress values. The study also concluded that the role of zygomatic implant is important as it will transmit the occlusal forces substituting the zygomatic process brace [30].

The role of zygomatic implants in the treatment of maxillectomy patients was continued to be investigated by Miyamoto et al. in 2010 [31]. In the study, the maxillary prosthesis with different positions and numbers of standard dental implants were examined through 3D FEA. Maxillary prosthesis was designed with two zygomatic implants placed on the affected side and two to three standard implants in the maxillary alveolar bone on the unaffected side. The result of

analysis demonstrated that zygomatic implants provided suitable stress dispersal to the zygomatic and craniofacial bone on the affected side.

3.5 Finite Element Analysis in Dentistry

Various methods or analyses exist and can be applied to investigate the biomechanical criteria in the field of dentistry like the mechanical stress and strain distribution within implants and bones. Photoelastic model studies, strain gauge analysis and FEA are among the methods that are broadly available to be conducted on [1, 32]. In the photoelastic model study, the results obtained are recorded photographically using a high-resolution camera in the field of a circular polariscope [33]. The values of stress and its locations will be evaluated visually and subjectively. One of the disadvantages of photoelastic study is the normal stresses within the material simulating the bone cannot be detected. Furthermore, the isotropic photoelastic material simulates the orthotropic material (bone).

The stress distribution within bone can also be evaluated using the strain gauge analysis. The strain gauge analysis involves the use of strain transducers that placed on the prosthesis or overdenture surfaces connected to the implant bodies [22]. This analysis can measure the relative forces on restoration and simulates more complex structure than in the photoelastic study. Moreover, the additional experimental information such as stress types and strain qualification can also be found through this analysis. If a study gives a high focus on system geometry and mechanical properties of biologic tissues, a 2D or 3D FEA is the best option to be chosen. However, the 2D FEA is not preferable because of invalidity of models representation [34, 35]. As instance, the 2D FEA fails to distinguish between cortical and cancellous bone. Therefore, the results from 2D FEA cannot be used extensively as a prediction tool because they show a significant difference to represent the realistic situation.

In FEA, researchers can predict the behaviour or pattern of stress distribution at bone-implant interface as well as around the apical part of implant body in cancellous bone [14]. Moreover, through FEA, the complicated geometry of bones or implants can be modelled and solved, in which cannot be done by analytical solution. A complex mechanical problem can be solved into several collections of much smaller and simpler domains or elements by using FEA. The shape function is used to explain and interpolate the field variables. Finite element analysis that is also known as a prediction tool of the models tested, which the approximated results obtained to the basic problem are determined based on variational principles. In other words, the whole body or entire domain solution provided by FEA is based on the combination of solution functions for each finite element. Therefore, since a dental implant-bone system consists of several components that are extremely complex geometrically, FEA is believed can provide as an appropriate solution to the models tested [36–39]. There is a necessity to divide the whole

domain into smaller elements by having a meshing process for the execution of analysis in the finite element method. Besides the mesh, elements and nodes creation, the other processes like boundary conditions determination is referred to as “discretization” of the problem domain [14].

Finite element analysis was introduced since 1960s to solve the structural problems in aerospace industry; however, it has been expanded in use in other fields like heat transfer, electromagnet, mass transport and fluid flow. The first application of FEA in implant dentistry started in 1976 by Weinstein et al. [14, 40]. Ever since, FEA was widely applied in that field.

As the human bone tissue modelling and its response to applied loading is the major difficulty in simulating the mechanical behaviour of dental implants, several assumptions have to be considered so that the modelling and solving process can be successfully completed. The interaction of implants and surrounding tissues is vitally important in determining the mechanical characterization of the interface, however, due to its complexity, major simplifications are commonly made. It is essential to know that the accuracy of FEA results with some assumptions could be significantly influenced. Among parameters that often being simplified are bone and implant detailed geometry, material properties, boundary conditions, loadings and bone-implant contact properties [14].

The selection of element types is crucial for the finite element modelling particularly in dentistry field since it involves the construction of detailed and complex geometry. Tetrahedral and hexahedral are among the types of element that have been widely used. The curvy and complex shapes are preferable to be modelled by using tetrahedral element, and it can be either first order (4 nodes) or second order (10 nodes). For the hexahedral, it is known to have better accuracy due to its nature of having relatively more degrees of freedom. However, the high number of nodes for this element (8 nodes or 16 nodes) has a higher tendency to distort that resulted in less efficiency of contact analysis.

The equivalent von Mises stress is often used in FEA to verify the behaviour of stress generated within implants because of the appropriateness and the validity of the von Mises theory of failure towards isotropic and ductile materials [41]. The von Mises stress is a scalar quantity that includes all the components of the stress tensor that represents the overall magnitude of the tensor in three-dimensional [42]. The stress can be expressed as;

$$\sigma_{von\ Mises} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad (3.1)$$

where σ_1 , σ_2 and σ_3 are the principal stress and $\sigma_1 > \sigma_2 > \sigma_3$

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Chapter 4

Finite Element Modelling

Abstract In this chapter, all methods involved to generate 3D finite element models are presented in detail. The finite element modelling initially started by the reconstruction of bone models and then followed by the development of implant models. The 3D anatomical model of craniofacial presented in this text was obtained by the original maxilla with a high degree of bone resorption. The simulated implantation procedure would be conducted to place the implants into bone site afterwards. The prepared models were assigned with material properties, contact parameters, boundary conditions and simulated loadings before proceeding to the analysis. The 3D FEA was then performed with the data of equivalent von Mises stress and displacements within the respective models were presented numerically and plotted in spectrum colouring scale.

Keywords Three-dimensional craniofacial model construction • Pre-surgical planning • Three-dimensional implant model construction • Virtual surgery simulation • Finite element analysis settings

4.1 Three-Dimensional Craniofacial Model Reconstruction

A series of CT image datasets of a real complete denture wearer (edentulous human craniofacial) with a high degree of maxillary bone resorption was utilised in the analysis to develop 3D models. The patient was a man with estimated age of more than 60 years that has experienced of wearing complete conventional dentures in upper and lower jaw. The CT images consisted of 460 slices at 0.7 mm intervals with a resolution of 0.7 mm/pixel were taken in the axial plane direction. The CT data were transferred through networks and saved in Digital Imaging and Communications in Medicine (DICOM) format for the next usage. The images

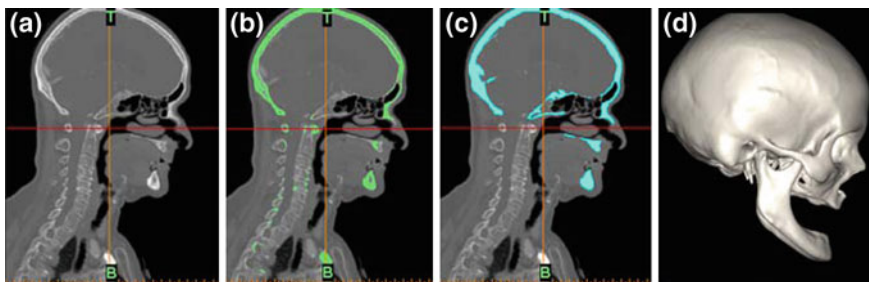


Fig. 4.1 Main steps involved in the reconstruction of 3D model of human craniofacial as shown in the right sagittal view (a) computed tomography image of craniofacial (b) mask layer (green) creation (c) edited mask layer and (d) 3D model of craniofacial

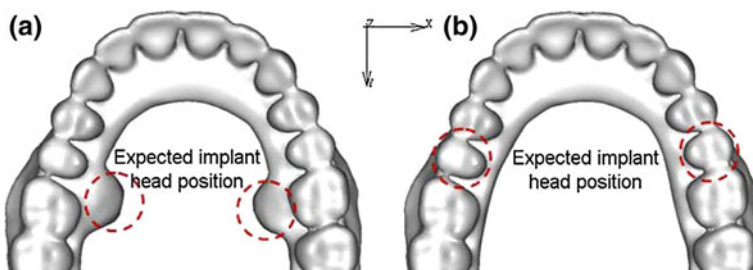


Fig. 4.2 (a) Three-dimensional model of partial framework design used in the (b) intrasinus and (c) extramaxillary approaches. The prosthesis was modelled as one part only (considered as “framework”) where the outer acrylic layer was ignored

were then transferred into an image-processing software, Mimics/Magics 10.01 (Materialise, Leuven, Belgium) to generate the 3D model of craniofacial. Cortical and cancellous bones were represented by voxels with different grey values in the CT images. The 2D CT image datasets were applied with thresholding feature by selecting compact bone set to create a mask. From the first mask creation, the images would be edited slice by slice based on the region of interest using segmentation tools. The edited mask would be then calculated to transform it into 3D model which produced by a surface triangularization technique. The surface of model can be smoothen and refined by applying smoothing tools with a particular value of iteration concerning the anatomical structure details. The main reconstruction processes of 3D craniofacial model are shown in Fig. 4.1.

Similar steps were repeated to reconstruct the 3D models of framework representing a partial prosthesis and mucosa soft tissues based on similar CT image datasets. The model of upper jaw denture was reconstructed carefully to maintain its design and geometry as closely as possible to the original patient's complete denture. Subsequently, a partial framework with flange was modelled with 1.52–3.46 mm in thickness (t), 12.45–19.06 mm in width (w) and 15.41–18.37 mm in height (h). There were two different designs of framework produced in which the

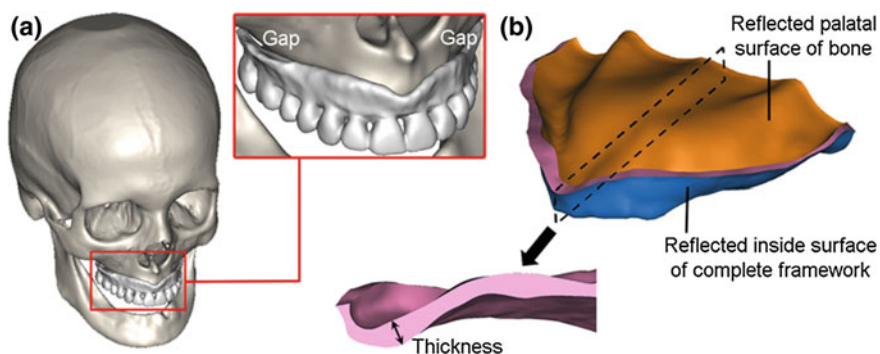


Fig. 4.3 The reconstruction of 3D model of soft tissue. (a) Gap existed along the maxillary arch between bone and framework. (b) Final model of soft tissue shown in the isometric and cross-sectional views

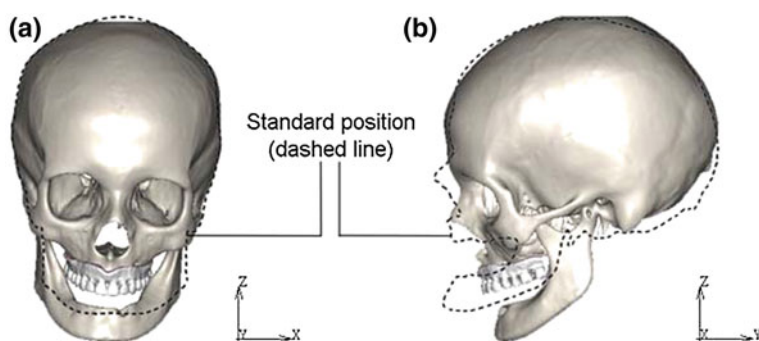


Fig. 4.4 Visualisation of reconstructed 3D model of craniofacial in the original position as shown in the (a) coronal and (b) *left* sagittal view

design for the intrasinus approach was bulkier than the one for the extramaxillary approach due to the expected emergence of implant heads slightly in the palatal area (Fig. 4.2). The gap existed along the maxillary arch between the palatal surface of bone and the inside surface of complete framework was used to develop a soft tissue model (Fig. 4.3). As a result, the soft tissue model had a thickness ranging from 2.16 (edentulous ridge) to 5.58 mm (hard palate) that lie within the ranges of the *in vivo* measurement done by Uchida et al., which is from 2.06 to 5.77 mm for male group [1].

All generated 3D models of craniofacial, framework and soft tissue were then visualised into their original position to determine the reference of coordinate system. It is important to make sure that the reconstructed models were in a standard position prior to the analysis for an accurate models representation. The models were probably not in the standard position or orientation as desired after scanning that could be due to the nature of the scan. In this text, it was clearly

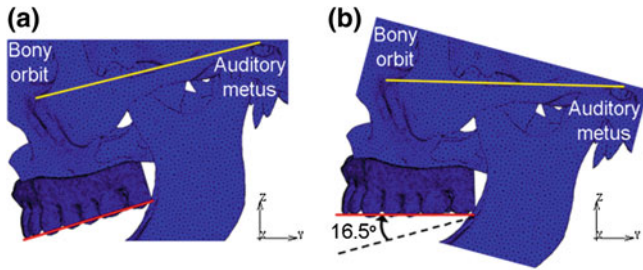


Fig. 4.5 Repositioning of craniofacial model from (a) original to (b) standard position based on the Frankfort horizontal (yellow) and occlusal planes (red)

shown that the craniofacial model was not in a standard position where the model was slightly inclined in a certain angle as viewed from coronal and sagittal planes (Fig. 4.4).

To position the craniofacial model into a standard orientation, the model has to be repositioned referring to the Frankfort horizontal plane. The Frankfort horizontal plane can be defined as a plane established by the lowest point on the margin of the right or left bony orbit and the highest point in the margin of the left or right auditory meatus. In addition, the occlusal plane was also determined at the incisal point and tips of the distobuccal cusps of the second lower molars. This plane forms an angle of 15–20° respected to the Frankfort horizontal plane. Since the direction of simulated masticatory force has to be perpendicular to the occlusal plane in the analysis, the occlusal plane was positioned to lie on the x -axis and y -axis or the x - y plane. The z -axis or implant axis is perpendicular to the occlusal plane. The models were then exported into a FEA software, MSC/MARC 2007 for the repositioning. As a result, the model was rotated about 16.5 and 4.4° along the x -axis and y -axis, respectively as depicted Fig. 4.5.

The selected region of interest was in the maxilla and the zygomatic bone on both sides, which also covered the infrazygomatic crest, anterior nasal spine, zygomatic process, temporal process, frontal process and the orbital floor surface (Fig. 4.6). The model dimensions were 111.9 mm in length, 46.5 mm in height and 52.4 mm in width. Both maxilla and zygomatic bone were reconstructed by consisting of two bone layers, cortical and cancellous bone as depicted in Fig. 4.7. The cortical layer of the maxilla had a thickness ranging from 0.50 to 1.17 mm covering the alveolar ridge and infrazygomatic crest regions with a thicker layer was obtained towards the maxillonasal and maxillozygomatic trajectories. Determination of the region of interest size is important so that the distribution of stresses to the end of bone segment will not impinge on the future results. According to Teixeira et al., a minimum bone length of 4.2 mm between implant body and segment end was relevant to ignore the stress variations around implant body [2]. The measurement on the models showed that the lengths were 11.28 and 20.61 mm for the intrasinus and extramaxillary approaches, respectively.

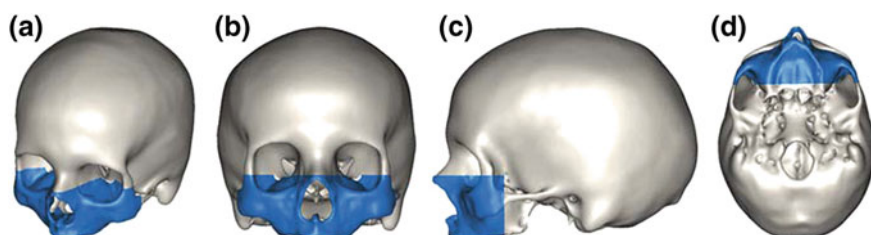


Fig. 4.6 Three-dimensional model of craniofacial with region of interest (blue colour) in the (a) isometric (b) coronal (c) left sagittal and (d) bottom axial view

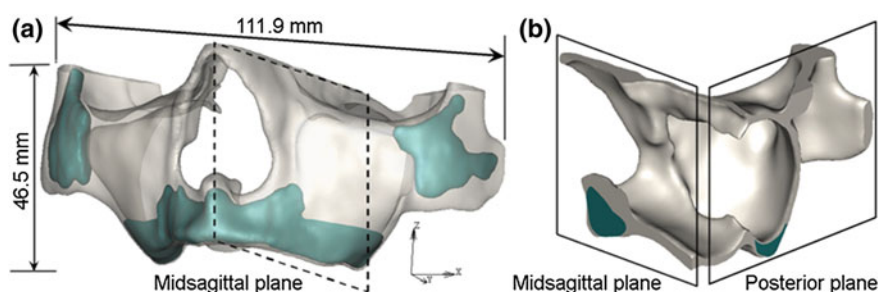


Fig. 4.7 Distribution of cancellous bone layer (dark green colour) shown in the (a) isometric and (b) cross-sectional views from the midsagittal and posterior planes

4.2 Pre-surgical Planning of Implants Fixation

The height (h) and width (w) of the atrophic maxilla to be treated were measured to determine a suitable approach for treatment, either through the use of zygomatic implants alone or in conjunction with conventional implants [3]. The measurement was performed by taking several readings based on the 2D CT images at posterior and anterior regions of the maxilla as depicted in Fig. 4.8. The exact dimension was obtained by taking the average value of the readings as presented in Table 4.1. Based on the measurements, the average height of the anterior, left and right posterior maxilla sections were 8.07, 5.50 and 2.61 mm, respectively. The width of the alveolar ridge in the molar region was 9.70 mm. These dimensions fulfilled edentulous jaw classification, described by Cawood and Howell, being Class III and Class V for the anterior and posterior maxillae, respectively [4]. Therefore, the patient could be treated with a zygomatic implant placed bilaterally in conjunction with two conventional dental implants in the anterior region.

To determine the length of zygomatic implants to be used, a measurement on bone at the respective areas (zygoma and maxilla) was done by using Mimics/Magics software. The procedure was started by defining the midsagittal plane (Md) that passing through three points; the midpoint of the superior margin of the nasal bone (N), subspinale and the incisive foramen (INF) [5]. A plane was created

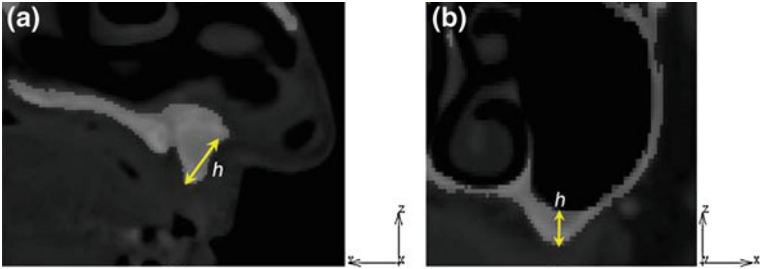


Fig. 4.8 (a) Anterior maxilla measurement (*sagittal* view) and (b) *left* posterior maxilla measurement (*coronal* view)

Table 4.1 Measurement data of the maxillary height

Location	Dimensions (mm)								Average
	1	2	3	4	5	6	7	8	
Anterior	8.18	8.14	8.14	8.14	8.14	8.18	8.18	7.42	8.07
Posterior (Left)	5.55	5.59	6.28	5.60	5.59	5.59	4.90	4.88	5.50
Posterior (Right)	2.70	2.86	2.77	2.80	2.09	2.07	2.78	2.80	2.61

through the bilateral infraorbital foramen (IF), perpendicular to the Md plane, and it was indicated as PTBIF. A point denoted as point A was shifted 5 mm towards the palatal region from the most inferior point of the alveolar process that crosses a line passing through the infraorbital foramen parallel to the Md plane [5]. This point being the starting point of the zygomatic implant insertion and the end point was determined by the jugale (Ju) point that located at the most depressed point of the transitional region from the lateral margin of the zygomaticofrontal process to the upper margin of the zygomaticotemporal process [5]. All landmarks and measurements are shown in Fig. 4.9. The distance between the crest of the maxillary alveolar process near the palate and the zygoma (A-Ju) was measured to determine the length of implant to be used. The angulation of the zygomatic implant was determined between the A-Ju distance and the PTBIF [5]. Results from the measurement were 48.9 mm for the length and 45.8° for the angle. The values recorded lie within the range of measurement done on cadavers by Uchida et al. where the range of values were 44.3–51.3 mm and 43.8–50.6° for the length and the angle, respectively [5]. Zygomatic implants are available in lengths from 31.5 to 51.5 mm with 5 mm steps. Accordingly, a 46.5 mm zygomatic implant is appropriate for this patient. The selection of longer implant (51.5 mm) is not practical since the apical portion could emerge in more dorsal direction towards the infratemporal fossa, which is should be avoided.

In the anterior region, conventional implants with a height of 10.0 mm were used as an optimal selection for D4-type bone. Also, the use of straight abutment is not practical in this case especially for the outcome of prosthesis position due to the morphology of maxilla or insufficient bone volume in the anterior region

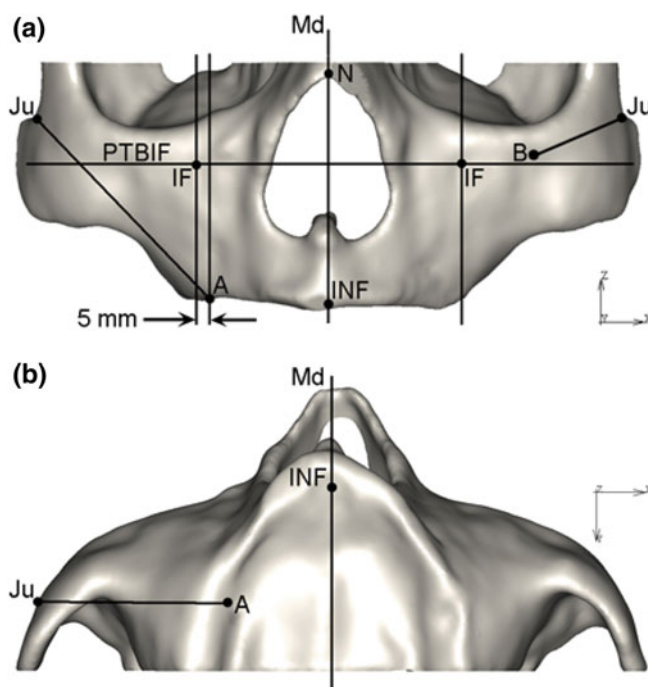


Fig. 4.9 Landmarks and measurements on bones for the pre-surgical planning of implant fixation shown in the (a) frontal and (b) axial views

(Class III). The use of angulated abutment (in particular degree of inclination) can avoid improper prosthesis angulation that can lead to discomfort for patients [3]. Moreover, it is a suitable restorative option to be considered when implants are not in the axial position. Patients could face difficulty in performing oral hygiene as well as affecting their smile by having inadequate prosthesis configuration [3].

4.3 Three-Dimensional Implant Models Construction

A 3D CAD software, SolidWorks 2009 (SolidWorks Corp., Concord, Massachusetts, USA) was utilised to develop the implant models [6]. The construction of implant model required a matched abutment to connect the implant body to the prosthesis. The implants were placed in the maxillary arch in spread-out configuration. Two conventional implants were placed in the lateral incisor region and one zygomatic implant was located per side in the first molar or second premolar region nonsymmetrically relevant to the respective surgical approaches investigated. In the analysis, three different implant configurations in terms of design geometry, diameter and length were modelled. Two 46.5 mm zygomatic implants

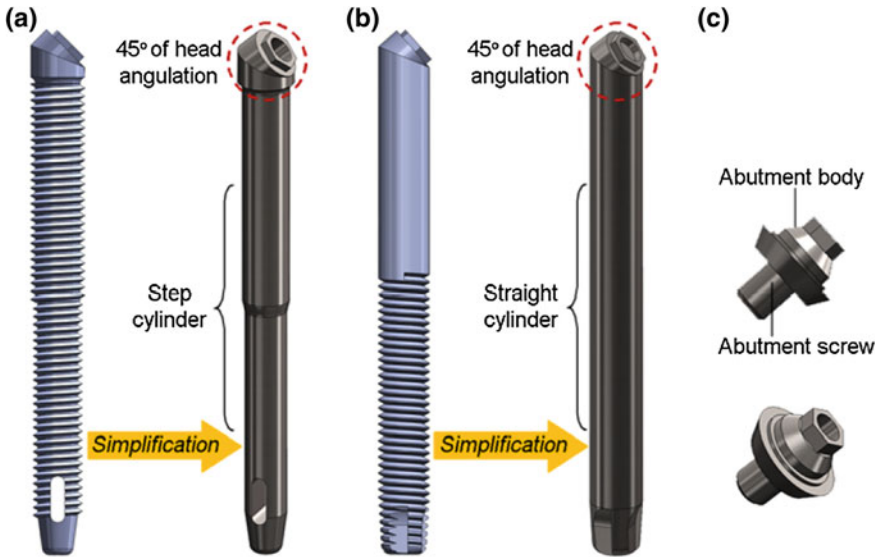


Fig. 4.10 Three-dimensional solid models of zygomatic implant body used in (a) intrasinus and (b) extramaxillary approach. (c) Three-dimensional solid model of straight multi-unit abutment

with 45° of angulated head, different diameter and thread distribution and two straight multi-unit abutments from Brånemark System® (Nobel Biocare AB, Göteborg, Sweden) were used [7]. The height of abutment was 3.5 mm. For the conventional dental implant, two 4.0 × 10.0 mm implants with an angled multi-unit abutment 30° for each implant was chosen from the same manufacturer with a height of 3.5 mm. Figs. 4.10 and 4.11 show the 3D solid model of implant bodies and matched abutments used in FEA. The abutment body and screw were modelled as one part.

All dimensions of implant bodies and implant abutments used in the analysis were based on the specifications of commercially available Brånemark System® implants, however, some geometries of implant body has been simplified. The original feature of implant body with thread distribution was ignored and simplified to that of a plain step and straight cylinder for zygomatic implant models in the intrasinus and extramaxillary approaches, respectively, and a plain taper cylinder for the conventional implant models. The thread distribution of all zygomatic and conventional implant designs were simulated via contact properties accordingly. The completed 3D solid implant designs were then transferred into other CAD software, Abaqus 6.9-1 (Dassault Systèmes Simulia Corp., Providence, RI, USA) to generate surface triangular elements, prior to the virtual surgery simulation. All implant models were meshed with 0.5 mm triangular element size, which is corresponding with the size used in Cattaneo et al. study [8].

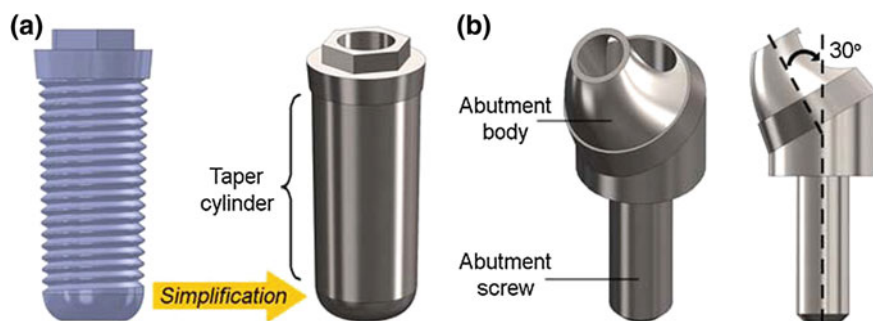


Fig. 4.11 Three-dimensional solid models of (a) conventional implant body and (b) angled multi-unit abutment 30° used in the analysis

4.4 Virtual Surgery Simulation

All reconstructed bone and implant models were individually exported as surface triangular elements in stereolithography (STL) format into Mimics/Magics software to perform the implantation procedures virtually. To refine the meshing of bone, soft tissue and framework models, the size of element was changed to that similar with implant models, which is 0.5 mm using all mesh refining tools provided. For convergence purposes, the chosen element size was almost three times smaller than the one suggested by Lin et.al.

To simulate the placement of zygomatic implants, both of the surgical approaches were in accordance with the procedures described by the Brånemark System[®] protocol that has been well-documented (see Sect. 2.5.3). In real situation, the mucosa soft tissue layer will be cut based on standard Le Fort 1 incision to expose the lateral surface of the maxilla as well as the infrazygomatic crest region up to the level of the zygoma. However, the incision was not simulated towards the soft tissue model since it was not a reasonable aspect to be concerned in the analysis. The fixation of zygomatic implants to bones in the intrasinus approach was simulated by mimicking the use of surgical guide without the realization of window at the lateral wall of the maxilla.

After the relevant anatomical structures had been identified, the respective virtual implant models would be selected and placed into the ideal bone sites. The conventional dental implant ($D = 4.0$ mm) and the zygomatic implant models ($D = 4.5$ mm at starting point and $D = 4.0$ mm at end point) were used. Two points were identified for the placement of the implants: the starting and end points. The point of incisura (end point) was identified prior to the placement of the zygomatic implant model into the bone site as the implant has to be installed as posteriorly as possible or close to the point. Simultaneously, the implant model must be assured to pass through the alveolar ridge (starting point), sinus cavity and ends in the zygoma by penetrating its cortical layer. Therefore, the zygomatic

implant model was directed laterally and in upward direction at 45° angulation from the vertical axis.

Several minor adjustments can be made to the position of the implant so that the implant head and apical part are surrounded by bones. It was important to make sure that the intermediate part of the implant body did not perforate the maxillary anterior wall and that the end of the implant body did not emerge in the infratemporal fossa. In clinical setting for the intrasinus approach, the sinus mucosa will be dissected from its inferior wall to prevent penetration by zygomatic implant body. The implant body had to be adjusted properly so that the implant platform could be positioned parallel to the occlusal plane to achieve a satisfactory prosthetic outcome. As a result, the position of the apical part of the implant was slightly diverging in the dorsal direction towards the infratemporal fossa. By using the function of “Boolean subtraction”, the unneeded volume exists between each entity i.e. bone and implant, was removed to form the prepared bone sites. Similar steps were repeated for inserting another zygomatic implant model into the opposite side.

The extramaxillary approach was introduced to simplify the earlier classical surgical approaches and was much easier to perform and simulate for the analysis in comparison to the intrasinus approach. Zygomatic implants of a different design ($D = 5.0$ mm at starting and end points) were placed externally into the maxilla and only anchored in the zygoma. The implants were placed as posteriorly as possible (3.0 mm from posterior vertical edge) in order to minimize the cantilever effect as well as for potential of implant additional if needed as described in clinical practices. The implant platform was also adjusted to be parallel to the occlusal plane and positioned close to the alveolar ridge crest on the maxillary arch before the placement of straight multi-unit abutment and framework.

For the conventional implants, they were located in the anterior region adjacent to the lateral incisors and canines. The rationale was to equally distribute the overall implant configuration within the arch to achieve optimal support for the stability of the prosthesis. The conventional implant ($L = 10.0$ mm) was placed 6.5 mm from the midsagittal plane in each bone side that angled posteriorly 30° . The implants had to be installed inclinely since there was only 8.0 mm of bone height available in the anterior region. This situation appeared consistent with literatures where the bone height of 5.0–8.0 mm could be treated with angled implants placement [9]. Two matched angulated abutment 30° were then placed on top of each implant body. The placement of the implant models were viewed in all directions of 2D and 3D visualisation, therefore, the position and orientation of each implant could be determined precisely. The 3D models allow a direct visualisation of the morphology of maxilla, level of maxillary sinus floor and bone volume for accurate implants placement. As a result, the final positions of zygomatic implants in the extramaxillary approach were found to have increased the framework cantilever length (23 % longer) and decreased the horizontal implant offset (45 % shorter) as well as A-P distance (41 % shorter) than the intrasinus approach. The outcomes of virtual surgery simulation are illustrated in Fig. 4.12 for both surgical approaches.

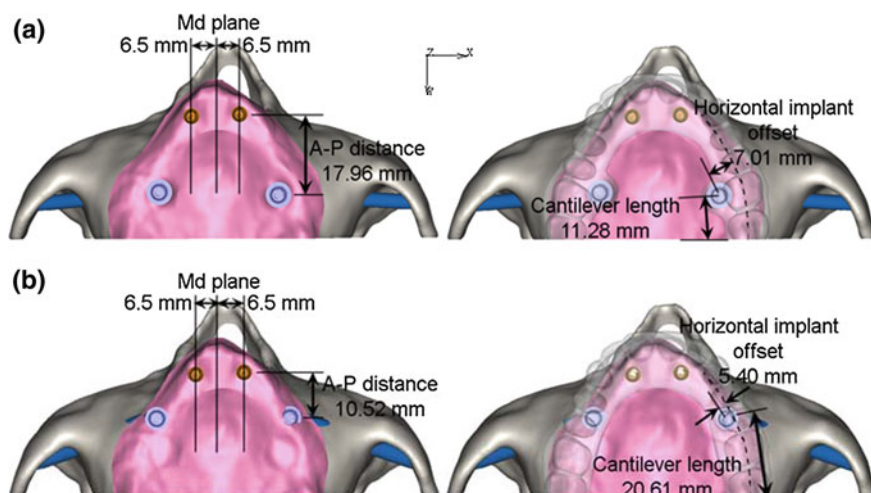


Fig. 4.12 The emergence of conventional implant abutments (orange) and zygomatic implant abutments (purple) on the maxillary arch for the (a) intrasinus and (b) extramaxillary approach

4.5 Finite Element Analysis (FEA)

4.5.1 Solid Meshed Models Generation

As the virtual surgery simulation had been completed, all 3D FEA models must be imported into the finite element software for pre-processing setting prior to the analysis. The FEA models comprise a set number of small elements that were generated through meshing process. The meshed element pattern must be identical among all models to avoid quantitative differences of stress values generated as well as to allow for comparison of different models. Therefore, a single mesh pattern has been assigned to the FEA models. All models had been converted from surface triangular into solid tetrahedral elements in the FEA software, MSC/MARC 2007 (MSC Software, Santa Ana, California, USA) with four nodes element type and three degrees of freedom. These elements are interconnected to each other by various numbers of discrete points that called nodes. The total number of elements for the intrasinus model was about 791,000, whereas the extramaxillary model had a total of 787,000 tetrahedral elements. For the total number of nodes, it gives about 196,000 and 194,000 nodes for the intrasinus and extramaxillary approaches, respectively. The number of elements and nodes in each model are shown in Table 4.2.

Table 4.2 The number of elements and nodes in each model

Model	Intrasinus		Extramaxillary	
	Elements	Nodes	Elements	Nodes
Cortical	388,719	97,974	386,612	97,547
Cancellous	94,730	24,082	94,788	23,928
Mucosa soft tissue	84,597	21,345	79,676	20,273
Framework	149,666	33,636	141,947	33,470
Angled multi-unit abutment 30°	6,344	1,820	6,344	1,820
Straight multi-unit abutment	7,037	2,060	7,021	1,898
Conventional implant body	8,529	2,277	8,529	2,277
Zygomatic implant body	51,376	12,633	51,637	13,021

4.5.2 Contact Modelling

For the contact parameter setting, the interface between implants and bones was not considered as fully osseointegrated as often stated in many previous dentistry FEA studies, in which therefore, the condition of the interface was not assumed to be as perfectly bonded. The friction coefficients, μ , for all contacting surfaces of implants and framework models were set to 0.3 to simulate the immediate loading condition corresponding with work done by Huang et al. [6]. The thread distributions of zygomatic implant designs were different for the two surgical approaches and were accordingly simulated via contact properties. The threaded part of the implant body for both intrasinus and extramaxillary approaches was assigned with a friction coefficient of 0.5 to represent its strong attachment to the bone [10]. Other than that, the contact surfaces between cortical-cancellous and cortical-mucosa soft tissue were assumed to be as perfectly bonded by merging the nodes between the two contacted models, and therefore, no frictional contacts were assigned. In general, there were a total of 12 and 14 contact bodies existed in the intrasinus and extramaxillary approach, respectively and were defined as deformable.

4.5.3 Material Properties Assignment

All materials for FEA models were assumed to be isotropic, homogenous and linearly elastic throughout the analysis. In nature, the cancellous bone is a highly porous structure, however, it had been modelled as continuum and solid structure similar to the cortical bone, with approximately 13 times lower value of modulus of elasticity simulating D4-type bone. The implants and abutments were made of titanium alloy (Ti6Al4V) whilst the framework was made of gold alloy. Two material properties were assigned to each model, which are Young's modulus and Poisson's ratio, for the execution and accurate analysis. The material properties of all models are defined in Table 4.3.

Table 4.3 Material properties used in FEA

Material	Young’s modulus, E (MPa)	Poisson’s ratio, ν	References
Cortical	13,400	0.30	[7, 11, 12]
Cancellous	1,000	0.30	[13]
Mucosa soft tissue	2.8	0.40	[14]
Framework	100,000	0.30	[7, 15]
Implants	110,000	0.33	[7, 11]

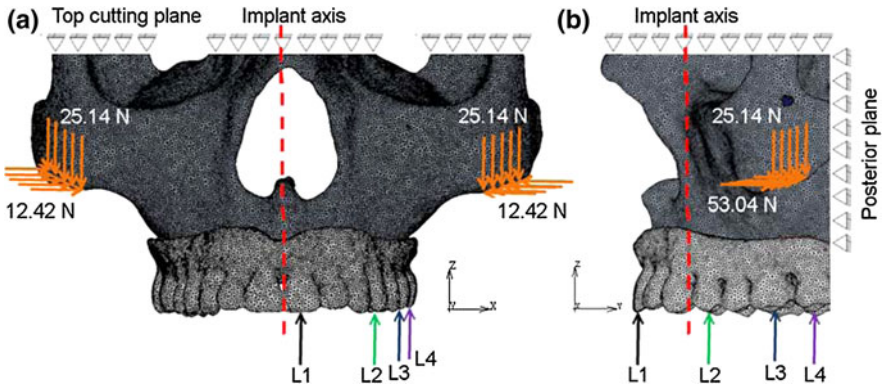


Fig. 4.13 Boundary conditions, masseter and vertical occlusal loadings at different loading locations as viewed from the (a) frontal and (b) sagittal planes

4.5.4 Boundary and Loading Conditions

Two types of loading were applied to the finite element models being simulated: occlusal and masseter loadings. The direction and magnitude of occlusal forces vary greatly between individuals and location of force application in the mouth. To simulate occlusal or masticatory force, the static vertical and oblique loads were applied. A vertical load of 150 N [7, 8] was applied at different locations on the framework surface as depicted in Fig. 4.13 to represent more realistic food positions during biting or chewing (see Chap. 5 for further details) [16, 17]. All vertical load conditions were applied in the z-axis, which is parallel to the standard implant axis [7, 8]. Besides, the oblique loads that consist of the combination of vertical and horizontal force components were also considered (see Chap. 6 for further details). For these loads, with similar force magnitude, they were applied in the first molar region inclined posteriorly 0, 15, 30 and 45° relative to the implant axis and 0, 15, 30 and 45° away from the sagittal plane as illustrated in Fig. 4.14 [16, 18]. This aimed to simulate the masticatory forces as much as possible. The selected region for inclined loading location was assumed to simulate the chewing centre. Besides, the posterior maxilla is being the region of interest to deliberate due to main functional area of masticatory activity found [19]. Consequently, a

Table 4.4 Occlusal load configurations

Load	Load 1 (L1)	Load 2 (L2)	Load 3 (L3)	Load 4 (L4)	Load 3a (L3a)	Load 3b (L3b)	Load 3c (L3c)	Load 3d (L3d)
Value (N)	150	150	150	150	150	150	150	150
Direction	Vertical	Vertical	Vertical	Vertical	Oblique 0°	Oblique 15°	Oblique 30°	Oblique 45°
Location	Central incisor	1 st Premolar	1 st Molar	2 nd Molar	1 st Molar	1 st Molar	1 st Molar	1 st Molar

Table 4.5 Vertical and horizontal force components for each oblique load

Load	Load 3a (L3a)	Load 3b (L3b)	Load 3c (L3c)	Load 3d (L3d)
Inclination	0°	15°	30°	45°
Vertical component (N)	$F_z = 150.00$	$F_z = 144.89$	$F_z = 129.90$	$F_z = 106.07$
Horizontal component (N)	$F_x = 0.00$ $F_y = -150.00$	$F_x = -77.65$ $F_y = -183.71$	$F_x = -150.00$ $F_y = -204.90$	$F_x = -212.13$ $F_y = -212.13$

total of eight conditions of occlusal loading were produced and all of them were individually applied on the top surface of framework as a point load on the left side of bone. Tables 4.4 and 4.5 show all occlusal loading configurations used in FEA that differs in terms of direction and location.

A simulated masseter load of 300 N [7, 8] with force components of -12.42 N along the x -axis, 53.04 N along the y -axis and -25.14 N along the z -axis was applied to the left side of the bone. For the right side, similar magnitude of forces were applied in the same direction, except for the x -axis force component. The simulated masseter load represented the masseter muscle action and was applied to the muscle attachment area on the zygomatic bone as a distributed load [7]. For the boundary conditions, the posterior (x - z plane) and top cutting planes (x - y plane) were constrained in the x , y and z directions to prevent any movements as depicted in Figs. 4.13 and 4.14.

4.6 Total Contact Area

The total contact area of bone-to-implant body is one of the most important factors in determining the primary implant stability. From thorough observation, the placement of zygomatic implants in bone by different surgical approaches was expected to give a significant difference in the total area of bone-implant contact surfaces generated. A manual calculation had been made by using FEA software to determine the percentage of mating surfaces for both cortical and cancellous bones to the zygomatic implant bodies. The total contact surfaces were calculated starting from the head to the tip of the implant body, which covers the entire implant insertion path. The results of calculation are shown in Fig. 4.15.

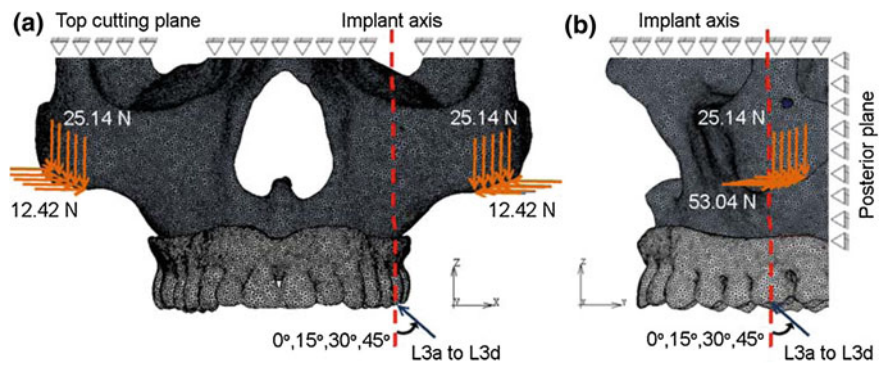
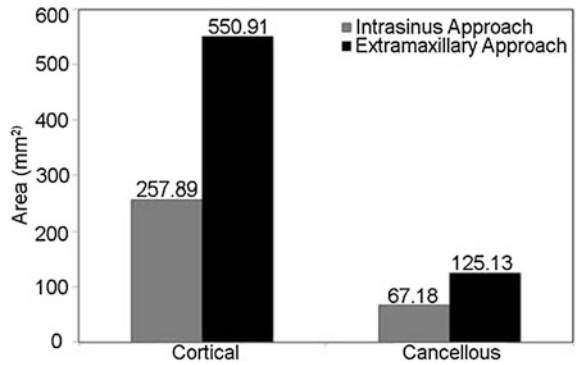


Fig. 4.14 Boundary conditions, masseter and oblique occlusal loadings in different loading directions as viewed from the (a) frontal and (b) sagittal planes

Fig. 4.15 Comparison of total area of mating surface between zygomatic implants and bones



From the graph, it is clearly shown that extramaxillary approach exhibited a higher total of bone-to-implant contact area compared to intrasinus approach. The cortical and cancellous bone-implant interfaces were increased by 53 and 46 %, respectively through extramaxillary approach. It was more likely two times increase in the total number of mating surfaces. For intrasinus approach, it was about 21 % of entire implant body surface that having contact with cortical and cancellous bones whereas 39 % for extramaxillary, considering zygomatic implant placement in both sides.

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Chapter 5

Bone and Prosthetic Component Responses in Various Occlusal Loading Locations

Abstract In this chapter, the data for equivalent von Mises stress (EQV) and resultant displacement within the bones and prosthetic components are presented and discussed numerically and also plotted in spectrum colouring scale. These indices are analysed for both intrasinus and extramaxillary approaches at different occlusal loading locations—central incisor (L1), 1st premolar (L2), 1st molar (L3) and 2nd molar (L4) regions. The resultant displacement magnitude was measured for the prosthetic components; framework and implants, owing to the difficulty of examining the direction of the framework and implants movement by merely looking at the stress results. Results showed that higher stress values were found within the bones and prosthetic components on working side for the extramaxillary as compared to the intrasinus approach, especially under the most posterior loading, L4 due to the cantilever effect. The prosthetic components in the extramaxillary also exhibited higher displacement magnitudes than those in the intrasinus when loading occurred in the anterior and the most posterior regions.

Keywords Mechanical stress distribution within the bones • Mechanical stress distribution within the framework • Mechanical stress distribution within the implants • Displacement of prosthetic components

5.1 Mechanical Stress Distribution Within the Bones, Framework and Implants

5.1.1 Mechanical Stress Distribution Within the Bones

A higher level of stress was expected within the cortical bone on the left side when the load was applied in posterior regions of the corresponding side at the 1st premolar (L2), 1st molar (L3) and 2nd molar (L4). As far as the stress within bone

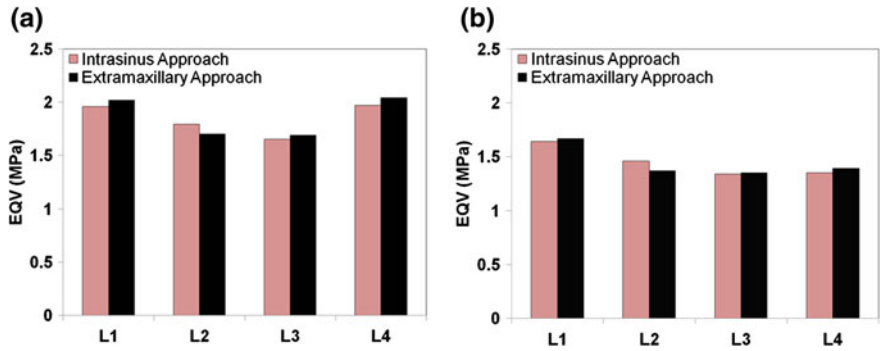


Fig. 5.1 Comparison of EQV magnitude within **a** cortical and **b** cancellous bones for both surgical approaches at different load locations

was concerned, the highest value was recorded for the most posterior loading (L4) in both the intrasinus and extramaxillary approaches. However, an unexpected situation was observed when a high magnitude of stress was generated with the application of an anterior load for both surgical approaches, when compared to 1st premolar and 1st molar loading. Figures 5.1a and 5.2 indicate that anterior load led to high average stress magnitude and left high stress localization within the cortical bone in the anterior nasal spine region. A similar pattern of stress was found in the cancellous bone wherein the stress values decreased as the load moved posteriorly (Fig. 5.1b). This finding is likely to be due to the limited area for stress dispersion at the anterior nasal spine without widely distributed to the surrounding area. On the contrary, the maximum stresses induced by the most posterior loading could be initially transferred to the alveolar bone and mainly absorbed by zygomatic implants, and subsequently dispersed to the zygoma. Both approaches seemed to have less significant discrepancy of average bones stress values, with extramaxillary approach exhibited a slightly higher magnitude of EQV within cortical and cancellous bone as compared to intrasinus approach in almost all load locations.

This finding is in agreement with the works done by Bonnet et al. and Daas et al. who reported that higher stress was observed in the molar region as compared to other regions (canine and incisor) [1, 2]. The results of this numerical analysis also supported the concept of a class 3-Lever wherein a higher magnitude of forces is required to lift the weight as the force moves nearer to the fulcrum. In clinical situations, the force, fulcrum and weight are represented by occlusal forces, the temporomandibular joint and food, respectively.

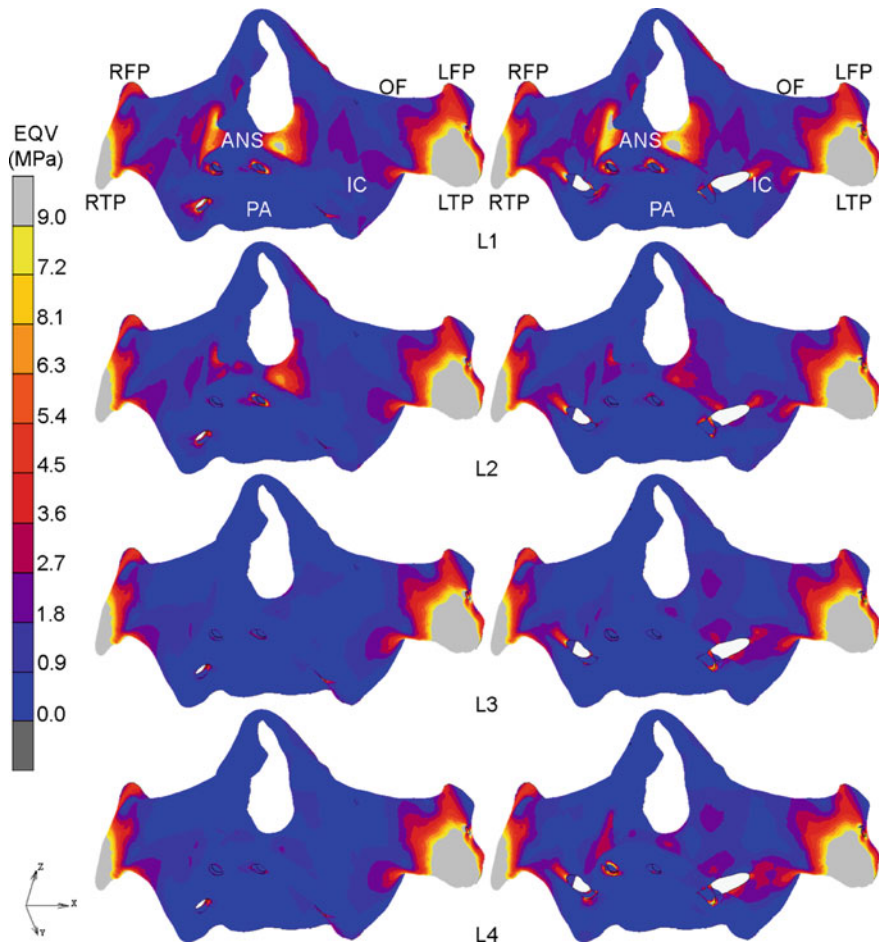
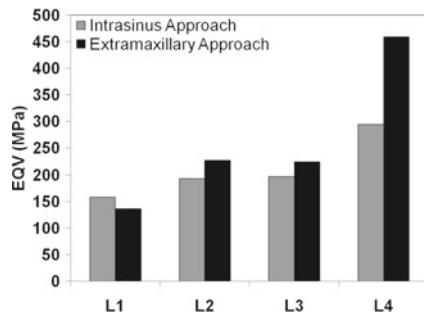


Fig. 5.2 Comparison of EQV distribution within cortical bone under L1 to L4 for the intrasinus and extramaxillary approach (left to right) as viewed from frontal (ANS Anterior nasal spine, IC Infrazygomatic crest, LFP Left frontal process, LTP Left temporal process, MSL Maxillary sinus lateral wall, OF Orbital floor, PA Palatal area, RFP Right frontal process, RTP Right temporal process)

5.1.2 Mechanical Stress Distribution Within the Framework

Again, the results of stress distribution within the framework indicated that posterior loads resulted in high stress magnitudes and concentration around the connection of framework-implants. As observed in intrasinus approach, the magnitude of EQV increased as loads moved posteriorly (158.00–294.27 MPa). This situation was also seen in extramaxillary approach where EQV magnitudes increased from 136.05 MPa up to 459.35 MPa (Fig. 5.3). The peak EQV value

Fig. 5.3 Comparison of EQV magnitude within the framework for both surgical approaches



within the framework was recorded under L4, with extramaxillary approach being 36 % higher than intrasinus. In comparison, the framework in extramaxillary demonstrated higher values of EQV than that in intrasinus approach (12–36 %) under almost all loading locations except for L1 (being 14% lower).

This outcome was parallel to the stress results obtained within the bodies of zygomatic implants wherein posterior loads were the major influencing factors. The load applied to the top surface of the framework in the molar region resulted in high stress concentration that could be due to resistance to high bending moments generated by the zygomatic implants. A balanced stress distribution was seen on the framework model when it was loaded anteriorly as shown in Fig. 5.4. A possible explanation for this observation is that there may be a progressive transfer of occlusal load from the load point to the surrounding conventional and zygomatic implants in the mesio-distal direction.

In order to easily differentiate between the implant models, two sets of symbols were used. The first symbol denotes the types of implants: “ZI” for the zygomatic implant and “CI” for the conventional implant. The second symbol indicates the location of the implants: “1” and “2” symbolises the placement of the implant in the left (working side) and right side (non-working side) of the bone model, respectively.

5.1.3 Mechanical Stress Distribution Within the Implants

Within both zygomatic implants investigated, it appears that the 2nd molar load (L4) configuration led to the highest stress values in ZI1 for both intrasinus (64.8 MPa) and extramaxillary approaches (91.3 MPa) as illustrated in Figs. 5.5a, b. The high stresses were mainly concentrated at the abutment-implant connection and spread out towards the coronal and intermediate parts of the implant body on the bucco-lingual side. The apical part seemed to have a smaller EQV dispersion than the coronal part, and the stress concentration region became wider as the applied load moved posteriorly (Figs. 5.6, 5.7).

In comparison, extramaxillary approach exhibited 30 % higher of maximum stress value generated within ZI1 than intrasinus approach. It is noteworthy that

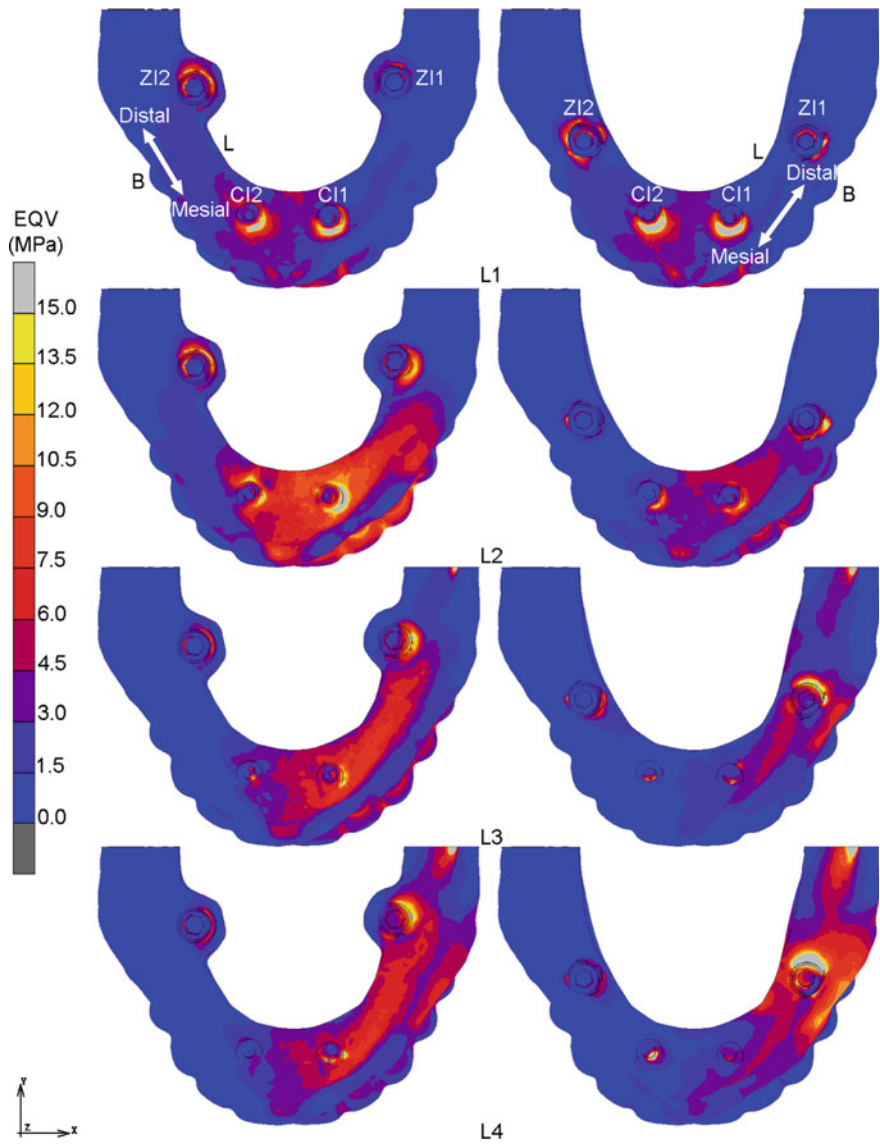


Fig. 5.4 Comparison of EQV distribution within the framework under L1 to L4 for the intrasinus and extramaxillary approach (*left to right*) as viewed from top axial (*B* Buccal, *L* Lingual)

the framework used in that approach had approximately two times longer distal extension of a cantilever when compared to the one used in the intrasinus approach, thus, increasing the bending moment generated as depicted in Fig. 4.12 (see Sect. 4.4). The cantilever effect is one of the crucial issues that cannot be compromised in implant-supported fixed prostheses and being the most important factor to influence the stress and displacement parameter generated in this analysis.

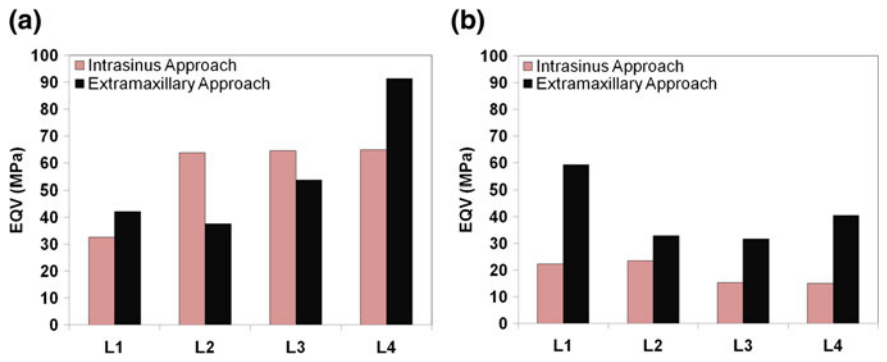


Fig. 5.5 Comparison of EQV magnitude within **a** ZI1 (working side) and **b** ZI2 (non-working side) for both surgical approaches

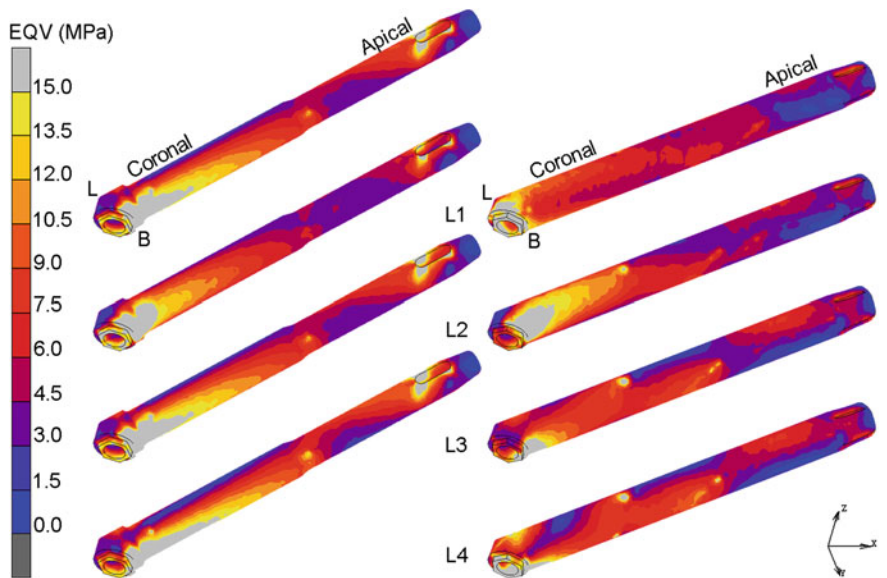


Fig. 5.6 Comparison of EQV distribution within ZI1 under L1 to L4 for the intrasinus and extramaxillary approach (*left to right*) as viewed from frontal

From mechanical perspective, the value of bending moment increased proportionally with the increase of load distance at constant load magnitudes. Rubo et al. drew similar conclusions that the increase of stress in implants is proportional to the increase of cantilever lengths [3]. In another study conducted by Bevilacqua et al., it was recommended that the use of shorter cantilevers, associated with distal tilted implant, could preserve prosthetic components from overload [4]. As shown in the analysis, it can thus be suggested that the influence of cantilever effects is much more significant in the extramaxillary approach than the horizontal implant offset for implant restoration.

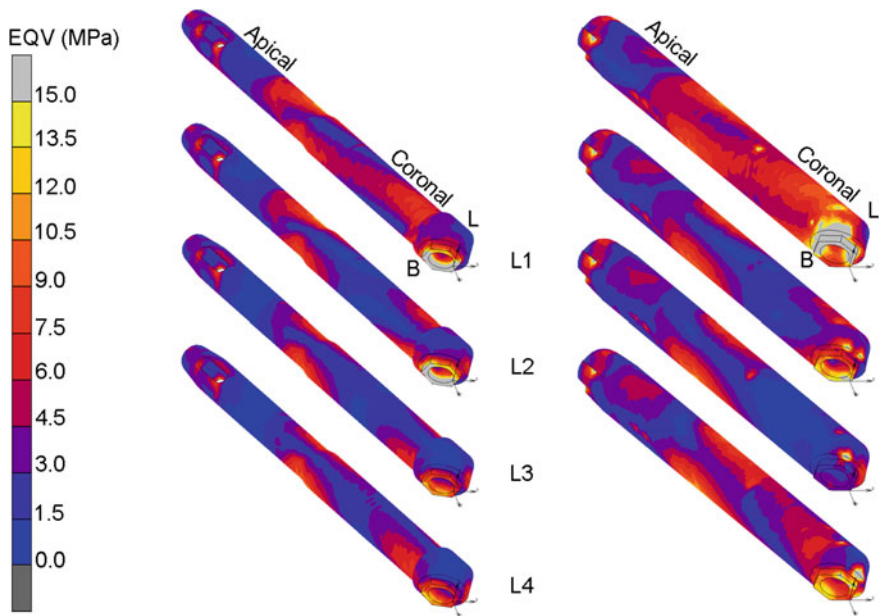


Fig. 5.7 Comparison of EQV distribution within ZI2 under L1 to L4 for the intrasinus and extramaxillary approach (*left to right*) as viewed from frontal

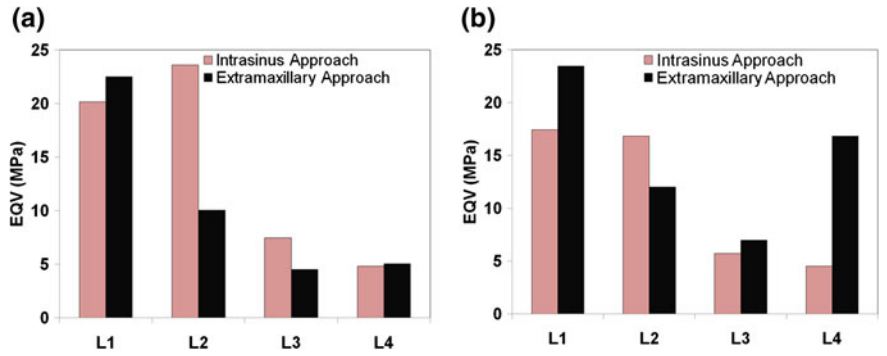


Fig. 5.8 Comparison of EQV magnitude within **a** CI1 (working side) and **b** CI2 (non-working side) for both surgical approaches

The findings of this numerical simulation also showed that the conventional implants placed in the premaxillary region were mostly responsible for the high stress produced by anterior load rather than by posterior loads. Both implants (CI1 and CI2) sustained high stress values (17.42–23.45 MPa) when loaded by anterior force with a larger stresses dispersion observed within the entire implant body than by posterior forces (Figs. 5.8a, b, 5.9 and 5.10). The conventional implant placed on the working side (CI1) via the intrasinus approach sustained higher stresses

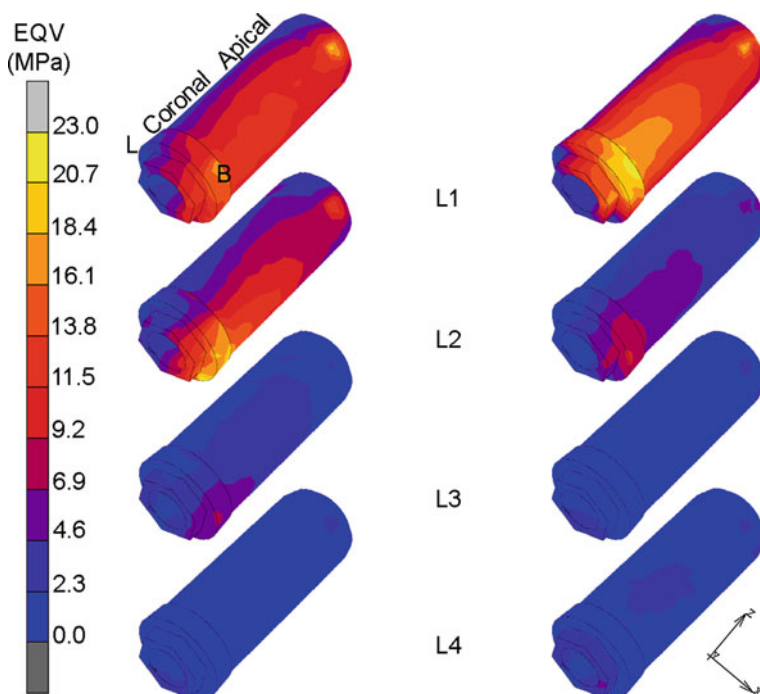


Fig. 5.9 Comparison of EQV distribution within CII under L1 to L4 for the intrasinus and extramaxillary approach (*left to right*) as viewed from frontal

under nearly all loading positions to retain the whole structure of restoration than what was seen in the extramaxillary approach. This finding could be attributed to the appearance of the posterior implants head, which is slightly out of the maxillary arch alignment, and headed towards the distal direction. This resulted in an increase of the A-P distance, causing lower retention provided by the framework to sustain interimplant loads, except when the load was applied on the 2nd molar (Fig. 5.11). Load applied in this region was better tolerated in the intrasinus approach as the force was more dispersed throughout the arch and the zygomatic implant body, unlike the extramaxillary approach, which was more affected by cantilever effects.

5.2 Displacement of Prosthetic Components

Depending on the location of load application, the magnitude of framework displacement decreased proportionally as the load applied posteriorly, except for L4 where the stresses were increased by 10 % and 54 % in intrasinus and extramaxillary approaches, respectively (Fig. 5.12). A larger displacement concentration area was produced at the anterior aspect of the framework model in both surgical

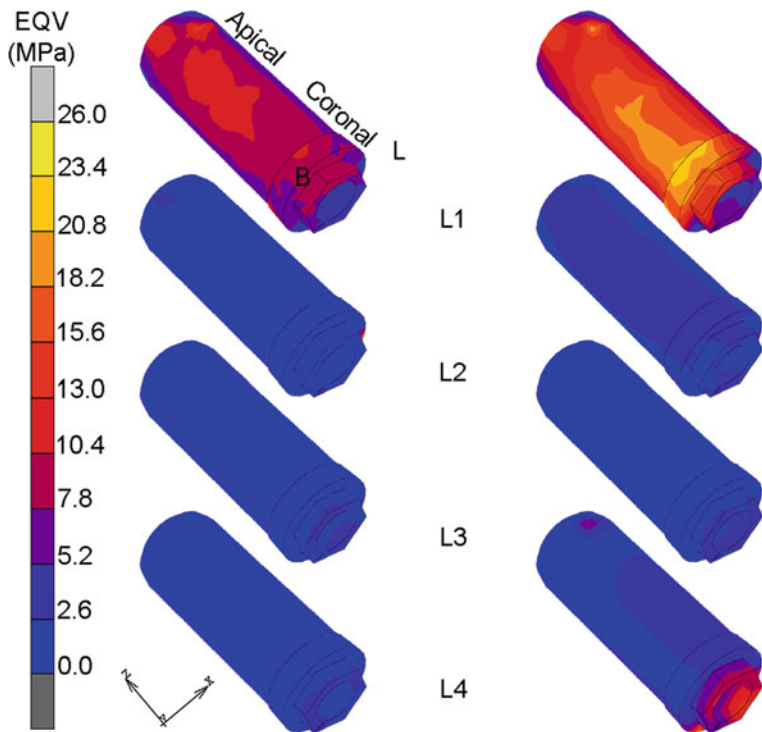


Fig. 5.10 Comparison of EQV distribution within CI2 under L1 to L4 for the intrasinus and extramaxillary approach (left to right) as viewed from frontal

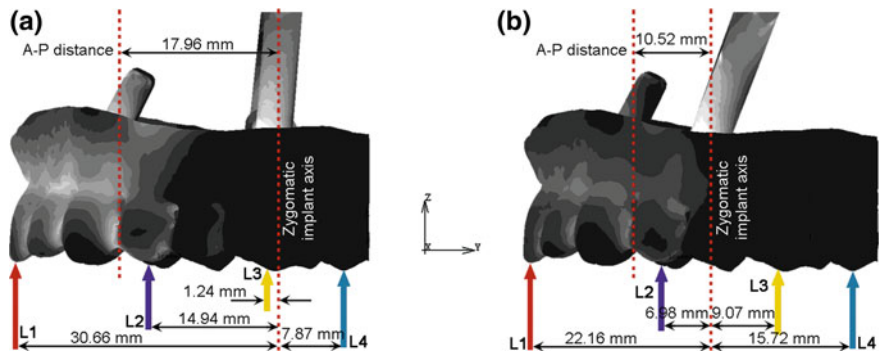


Fig. 5.11 A-P distance and the distance of each loading point to zygomatic implant axis for **a** intrasinus and **b** extramaxillary approach as viewed from sagittal

approaches. It could mean that the framework had a higher tendency to displace superiorly starting from the anterior aspect particularly at the center of arch when it was subjected with L1. This could be better explained by the rocking motion of

Fig. 5.12 Comparison of maximum displacement magnitude of framework for both approaches at different load locations

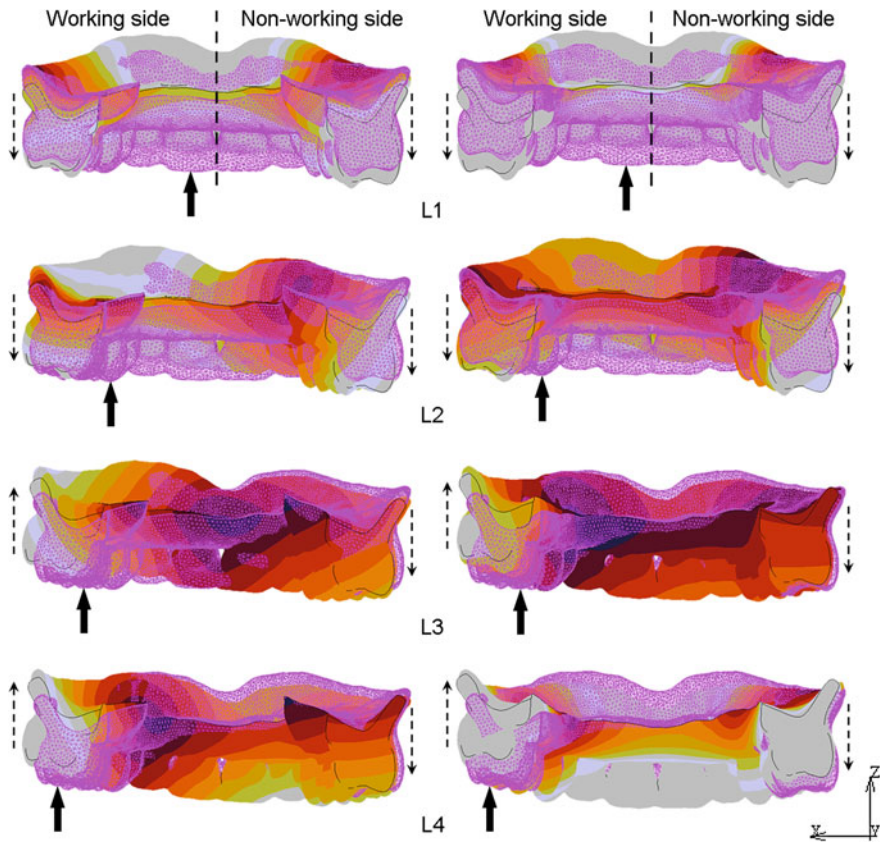
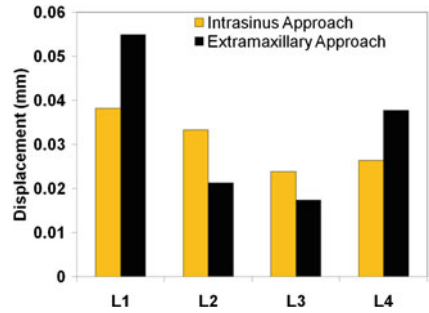


Fig. 5.13 Posterior view of framework motion in the intrasinus and extramaxillary approach (*left to right*) on L1 to L4 with deformation magnification factor of 100. The largest displacement of framework occurred in the z-axis. For L1, it could be seen that both sides showed an approximately symmetrical drop. Concerning position L2, both sides of the framework were dropping with greater amplitude found on the non-working side. For position L3 and L4, the working side of the framework was shifted up more under the action of the load. A swing of the framework around an axis could be noted. In intrasinus approach, the rocking motion was less effective for L1 and L4 as compared to extramaxillary

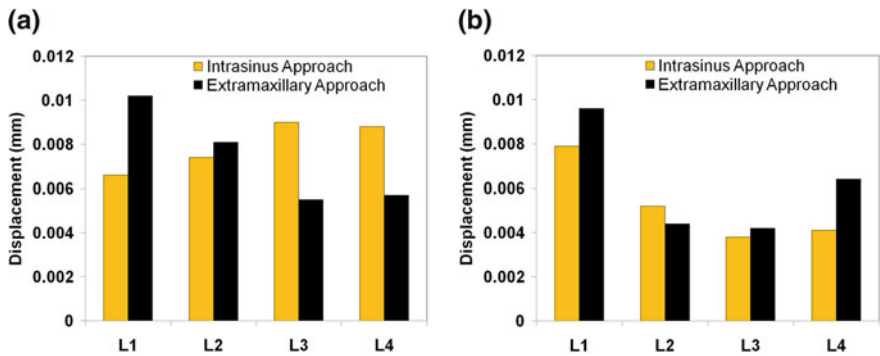


Fig. 5.14 Comparison of maximum displacement magnitude of **a** ZI1 (working side) and **b** ZI2 (non-working side) for both approaches at different load locations

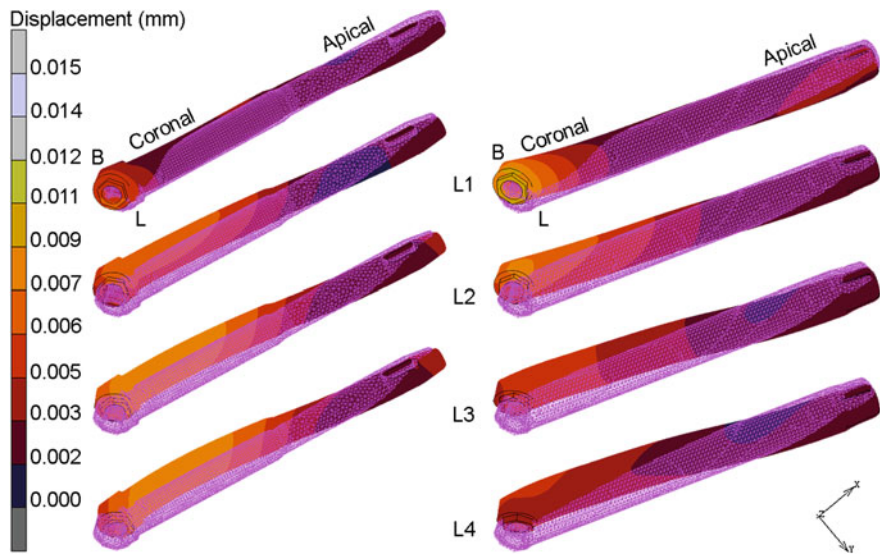


Fig. 5.15 Comparison of displacement pattern of ZI1 under L1 to L4 for the intrasinus and extramaxillary approach (*left to right*) as viewed from bottom

framework after loading with deformation scaling as shown in Fig. 5.13. Generally, extramaxillary left an effective influence on the framework displacement than intrasinus especially when the model was applied with the anterior load (L1) and the most posterior load (L4) with approximately 30 % higher. However, the reverse was seen under 1st premolar (L2) and 1st molar load (L3) where intrasinus approach seemed to record a higher displacement magnitude of the framework compared to extramaxillary with 36 % and 27 % difference, respectively.

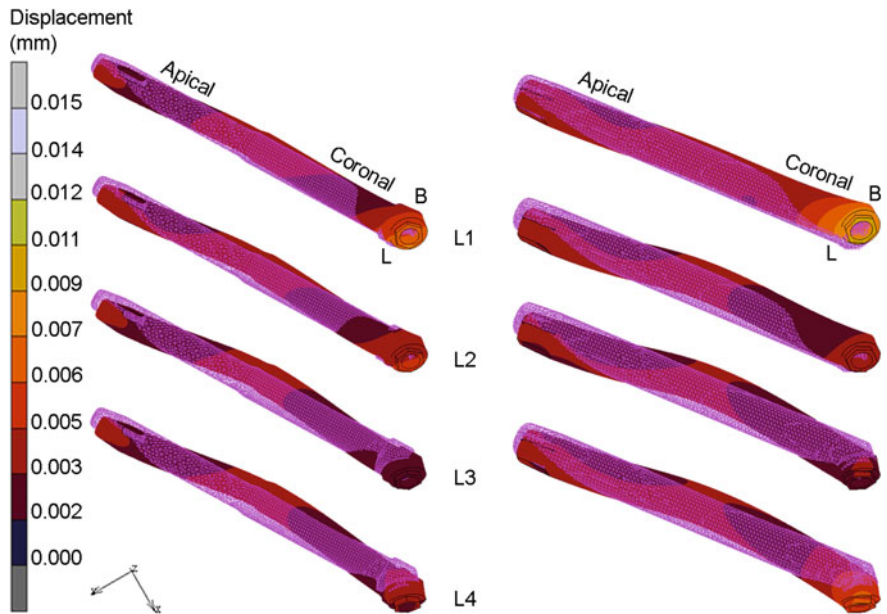


Fig. 5.16 Comparison of displacement pattern of ZI2 under L1 to L4 for the intrasinus and extramaxillary approach (*left to right*) as viewed from bottom

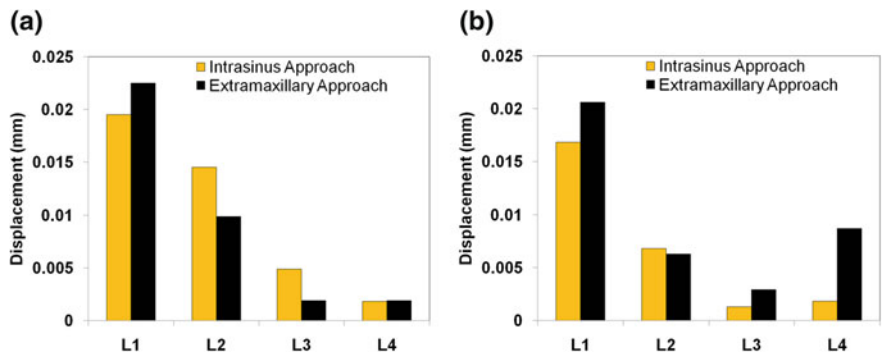


Fig. 5.17 Comparison of maximum displacement magnitude of **a** CI1 (working side) and **b** CI2 (non-working side) for both approaches at different load locations

Concerning the zygomatic implant application, it was observed that when posterior loads were applied, ZI1 had a higher potential to displace in intrasinus approach and the reverse was seen in extramaxillary (Fig. 5.14a). The maximum implant displacement was found under L1 (0.0102 mm) and L3 (0.009 mm) for the extramaxillary and intrasinus approaches, respectively. As illustrated in Figs. 5.15 and 5.16, a wide displacement concentration area was developed,

Fig. 5.18 Comparison of displacement pattern of CI1 under L1 to L4 for the intrasinus and extramaxillary approach (*left to right*) as viewed from frontal

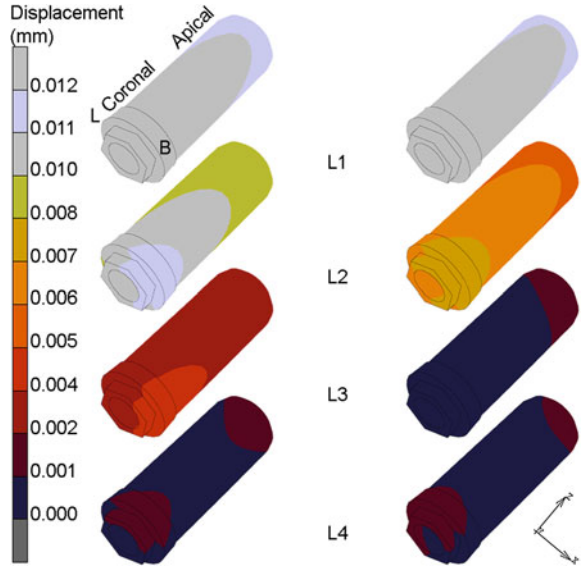
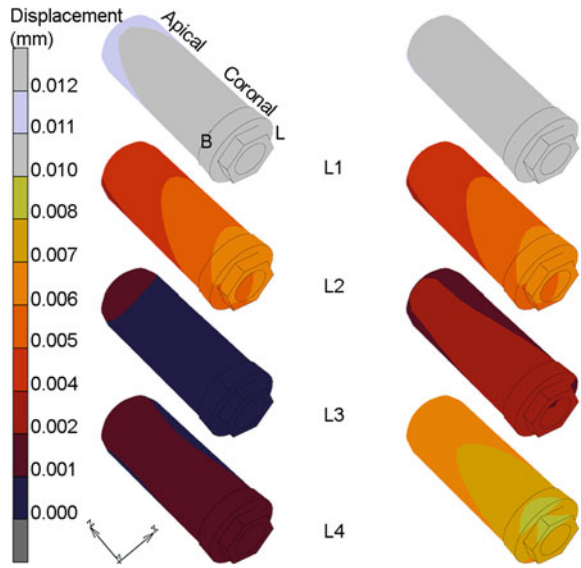


Fig. 5.19 Comparison of displacement pattern of CI2 under L1 to L4 for the intrasinus and extramaxillary approach (*left to right*) as viewed from frontal



starting from the implant-abutment connection in the coronal part and spreading out towards the apical part of the implant body, indicating a low tendency for the zygomatic implant body to deform at the intermediate and apical portion in both surgical approaches. For another zygomatic implant located in the right side (ZI2), it can be seen that anterior loading (L1) had contributed in the highest displacement magnitude generated for both approaches with extramaxillary exhibited

18 % higher than intrasinus (Fig. 5.14b). Although displacement values decreased as loading moved posteriorly, this was not evident in L4 where the values were increased up to 0.041 mm and 0.064 mm for the intrasinus and extramaxillary approach, respectively.

A similar outcome was found within implants placed in the anterior region excluding CII. The CII seemed to less displace proportionally as the applied loads moved towards the posterior region (Figs. 5.17a, b, 5.18 and 5.19). The anterior loading seemed to considerably increase the magnitude of zygomatic implant displacement in the extramaxillary approach as the implant body was only supported and accommodated by the outer surfaces of the maxilla. This result could be explained by the lack of bony support provided at the coronal portion of the implant body to resist loads in the buccal direction. A different pattern of displacement was observed in the intrasinus approach as the zygomatic implant head was highly restricted by the alveolar bone in the bucco-lingual and mesio-distal directions.

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Chapter 6

Bone and Prosthetic Component Responses in Various Occlusal Loading Directions

Abstract In this chapter, the data for equivalent von Mises stress (EQV) and resultant displacement generated within bones and prosthetic components are presented and discussed for both intrasinus and extramaxillary approaches in different occlusal loading directions. There are four different occlusal loading inclinations have been considered, 0 (L3a), 15 (L3b), 30 (L3c) and 45° (L3d), respected to the standard implant axis. The results of analysis have also been compared with the EQV and resultant displacement data obtained by the vertical occlusal loading (L3), at similar loading location. Results showed that the oblique occlusal loading with horizontal components produced higher magnitude of stress or displacement than the pure vertical loading. The bones and prosthetic components exhibited higher stress magnitude for the intrasinus approach compared to the extramaxillary under almost all loading inclinations. However, the results of displacement showed otherwise where the framework and implants in the extramaxillary generated higher displacement values than those in the intrasinus.

Keywords Mechanical stress distribution within the bones • Mechanical stress distribution within the framework • Mechanical stress distribution within the implants • Displacement of prosthetic components

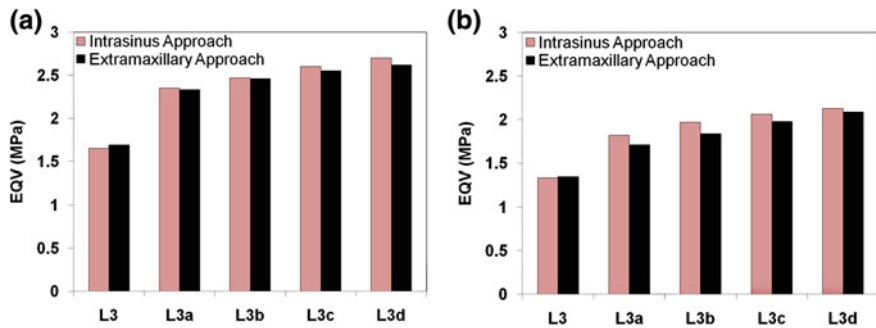


Fig. 6.1 Comparison of EQV magnitude within (a) cortical bone and (b) cancellous bone for both surgical approaches at different load directions

6.1 Mechanical Stress Distribution Within the Bones, Framework and Implants

6.1.1 Mechanical Stress Distribution Within the Bones

It was detected that the oblique loads (L3a to L3d) had significantly increased the average EQV values within the entire cortical and cancellous bone as compared to the pure vertical load (L3) in both intrasinus and extramaxillary approaches, at the similar point of load application (Fig. 6.1a and b). In general, the values of EQV were raised proportionally with the increase in force components angle. Within all models tested, the highest average cortical bone stress in intrasinus was found about 3 % higher than extramaxillary approach, generated under L3d. Under the same load, intrasinus approach also exhibited 2 % higher of maximum EQV value than extramaxillary generated within the cancellous bone. It could be showed that both approaches seemed to have less significant discrepancy of average bones stress values, with intrasinus approach recorded a slightly higher stress than extramaxillary, generally. The maximum EQV level was found on the cortical layer of zygomatic bone in both approaches for each load inclination, approximately 118 MPa and 138 MPa in intrasinus and extramaxillary approach, respectively. In the cancellous bone, a more significant visualization of stress dispersion was found in the maxilla than in the zygoma.

Figure 6.2 shows the stresses were uniformly distributed in the zygoma in two main directions, towards the temporal and frontal processes. Stresses were more gradually and largely distributed at the maxillary sinus lateral wall for extramaxillary as compared to intrasinus approach. The stresses were also tended to be generated over orbital floors and infratemporal fossae region. A wider stress concentration region was developed at the alveolar ridge bone which was then predominantly transferred towards the palatal area and infrazygomatic crest region in the bucco-lingual side, at surrounding maxilla region when the models were loaded by oblique forces.

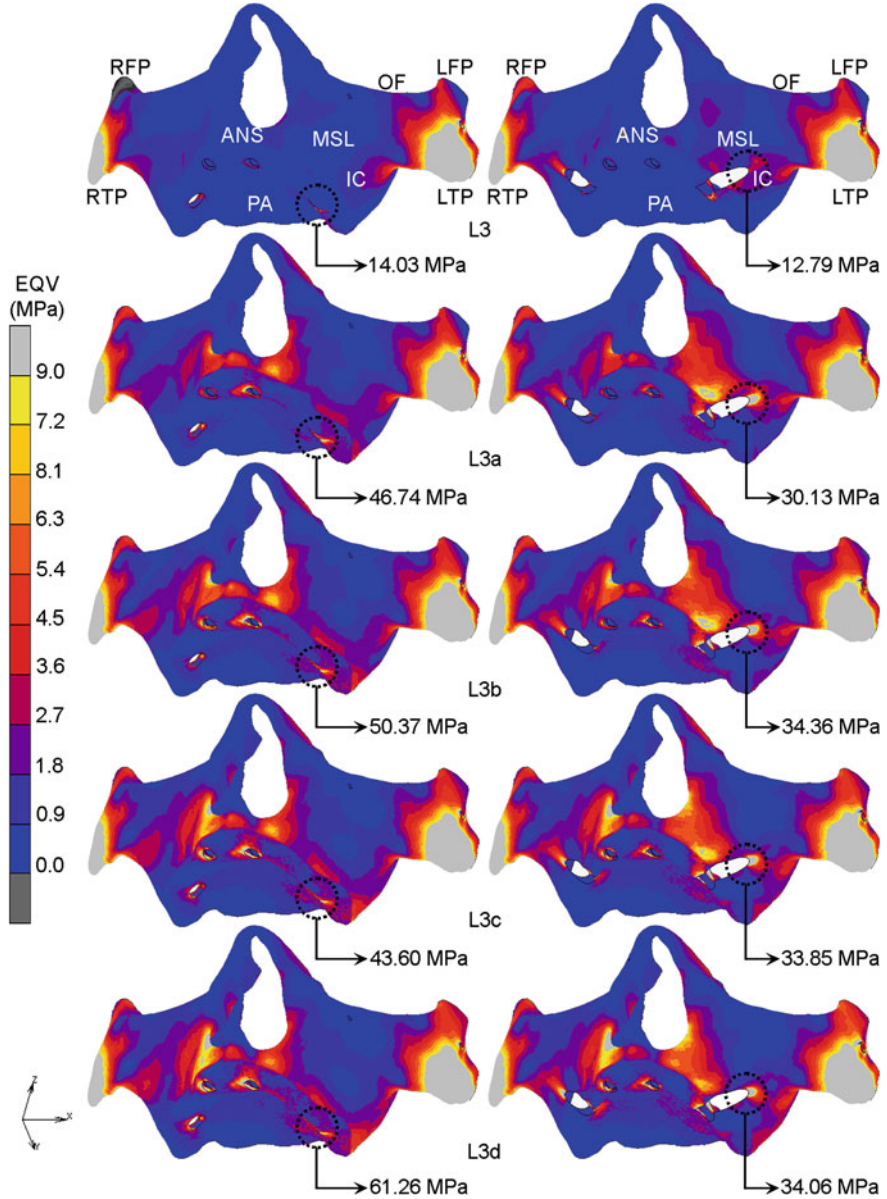


Fig. 6.2 Comparison of EQV distribution within cortical bone under L3 to L3d for the intrasinus and extramaxillary approach (left to right) as viewed from frontal (ANS Anterior nasal spine, IC Infrazygomatic crest, LFP Left frontal process, LTP Left temporal process, MSL Maxillary sinus lateral wall, OF Orbital floor, PA Palatal area, RFP Right frontal process, RTP Right temporal process)

Regarding the EQV pattern at the maxillopterygoid area, high stresses (14.03–61.26 MPa) were mainly concentrated at the alveolar crest region around the neck of implant body in intrasinus approach. The presence of opening path for the implant placement at the crestal region adjacent to the applied loading location in intrasinus approach increased the strength of alveolar bone to retain the implant position, thus, resulting in high stress concentration. For the extramaxillary approach, the location of opening path for implant insertion was in the second premolar region, which was further away from the loading point. This resulted in an evenly distributed stress within the bone around the first molar.

The high stresses generated could also be associated to the influence of total contact area between implant body and bone tissues. According to Javed et al., the threaded implant design could increase the primary stability by reducing the micromovement of implant [1, 2]. The zygomatic implant used in intrasinus approach is likely to have a high contact area as the implant surface area increases due to the thread along the implant body. However, the threaded part was ignored through the preparation of FEA models and has been simulated via friction coefficient in contact properties modelling to represent a strong attachment to bones (see Sect. 4.5.2). The implant-bone contact had occurred at the alveolar ridge, slightly in the palatal aspect and at the jugale point region of zygoma, which has resulted in a smaller mating surface than that of extramaxillary approach. The percentage of bone-implant contact area for the extramaxillary approach was higher by the placement of implant body externally to the maxilla particularly outside the maxillary sinus wall and end up in the zygoma (see Sect. 4.6). It is interesting to note that the coronal part of implant body had no threads to avoid infections of the soft tissue [3]. However, the insertion path of zygomatic implant had increased the contact area of implant body to bone and therefore reduced the level of stress within the bones.

The findings, however, found that areas surrounding the anterior nasal spine and the maxillary sinus wall in extramaxillary approach, sustained more stresses as compared to the one in intrasinus approach with largely stress widespread due to the instability of implant body and the path of load transfer. More stresses localised (12.79–34.36 MPa) at the edges of the maxilla relevant to the coronal part of implant body. The force passed through the framework, soft tissue, zygomatic implant body and then widely dissipated in the maxilla and the surrounding areas. The high bone stress at the maxillary edges around the coronal portion of implant body might be due to large rotational effects from implant body caused by torque generated. As the distance of zygomatic implant head to the loading point (1st molar region) is longer than those in the intrasinus approach, the magnitude of torque produced increases proportionally, leaving behind a high stress level on the surrounding bone. Another possible explanation for this is that the existence of sharp edges of the maxilla relative to the placement of implant. The high stress value in the maxilla is a concern because it could lead to bone loss or resorption in a long-term treatment [4–10]. It is important to prevent overloading since it could make bone more fragile by destructing implant-bone osseointegration and lead to fatigue failure of the implant [6, 11].

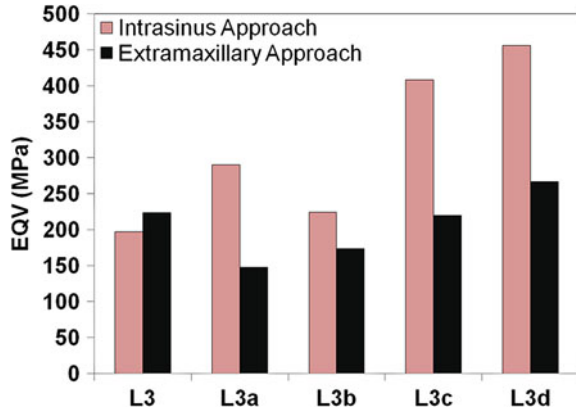
A higher density of cortical bone of the maxilla compared to cancellous bone (see Sect. 2.1) is the factor of high magnitudes of stress produced, which provides better resistance to deformation [4, 12]. Based on literature, the mechanical stresses started to be generated and concentrated when two materials with different properties (Young's modulus) had contacted each other after they were loaded [8, 13]. In this numerical simulation, the first part that the implant (high modulus of elasticity) met with is soft tissue (low modulus of elasticity), however, there was no significant result of stress observed. The next layer that contacted with the implant was the crestal region of cortical bone that having higher modulus of elasticity than cancellous bone and soft tissue. It absorbed most of the stresses transferred from the implant body [8, 12, 14, 15].

Most of the stresses produced from simulated occlusal loading were sustained by the zygoma and appeared to be less dependent on the maxillary anchorage. These results were in agreement with the findings of Ujigawa et al. who reported that the applied loadings were transferred through the infra-zygomatic crest and directed into the temporal and frontal processes of zygomatic bone [16]. In a study done by Yushino et al. it was also agreed that the masticatory loading was primarily transmitted into the zygomatic bone [17]. Furthermore, the present findings seem to be consistent with other researches that the zygoma was claimed to absorb most of the posterior loads [18, 19]. The occlusal forces were dissipated peripherally to the surrounding bony structures through three major trajectories; maxillonasal, maxillozygomatic and maxillopterygoid [20]. The stress dispersion to the orbital floor around the lacrimal bone and the frontal process was also confirmed, however, it was just in minimal.

The magnitude of maximum stress generated within the cortical layer of zygomatic bone for both intrasinus and extramaxillary approaches exceeded the yield strength of cortical bone, 69 MPa [21]. However, the percentage of nodal stress did not cover a large volume that could result in bone failure. The percentage of nodal stress higher than 69 MPa was only about 0.1 % for both surgical approaches.

The numerical results of the analysis showed that vertical and oblique loads resulted in different stress and displacement patterns within all models for the intrasinus and extramaxillary approach. The role of horizontal component in oblique load cannot be compromised since it has resulted in greater stress values and concentration within the bones specifically around the implant body than the pure vertical load. There was evidence where the bone remodelling has a strong correlation with the generated equivalent stresses. As discussed by Barbier et al., the horizontal component plays a major role in determining the difference degree of bone remodelling compared to axial loads. Therefore, the effect of horizontal load should be avoided because the excessive load could induce the progressive stresses increase and end up with the mechanical failure risk of implants. In general, the oblique load effect is approximately two times higher than the vertical load by considering the mean value of EQV generated within all models tested in this analysis.

Fig. 6.3 Comparison of EQV magnitude within the framework for both surgical approaches



6.1.2 Mechanical Stress Distribution Within the Framework

Also, in general, the application of oblique loads had influenced a higher stress value within the framework as compared to the vertical load in both approaches as shown in Fig. 6.3. Particularly, the framework model in intrasinus approach seemed to record a higher percentage of EQV increase than extramaxillary when it was obliquely loaded, which is about 43, while extramaxillary was only recorded about 8 % increase. As the force inclination increased, the magnitudes of EQV will increase, too. In comparison, extramaxillary approach showed a higher EQV level than intrasinus with 12 % increase when vertical load was applied at similar load location. A larger stress dispersion region was created when the model exerted by oblique loads which strongly concentrated at the framework-implant connection in both surgical approaches. The developed stress concentration area was seemed to become smaller as the angle of force components increased respected to the implant axis. This situation was observed in both intrasinus and extramaxillary approaches as the widest stress intensity region was found under L3a (Fig. 6.4).

6.1.3 Mechanical Stress Distribution Within the Implants

As illustrated in Figs. 6.5a, b and 6.6a, when the results of EQV within the implants are examined generally, it is observed that the stress values were significantly decreased as the angle of load increased as shown in both intrasinus and extramaxillary approaches, however, the stresses were slightly increased back under L3d. In contrast, the stress values within CI2 on the non-working side were kept increased proportional to loading inclinations, as illustrated in Fig. 6.6b. Concerning the different load directions, the highest EQV was recorded under L3a for both zygomatic implants with intrasinus exhibited 28 and 7 % higher stress

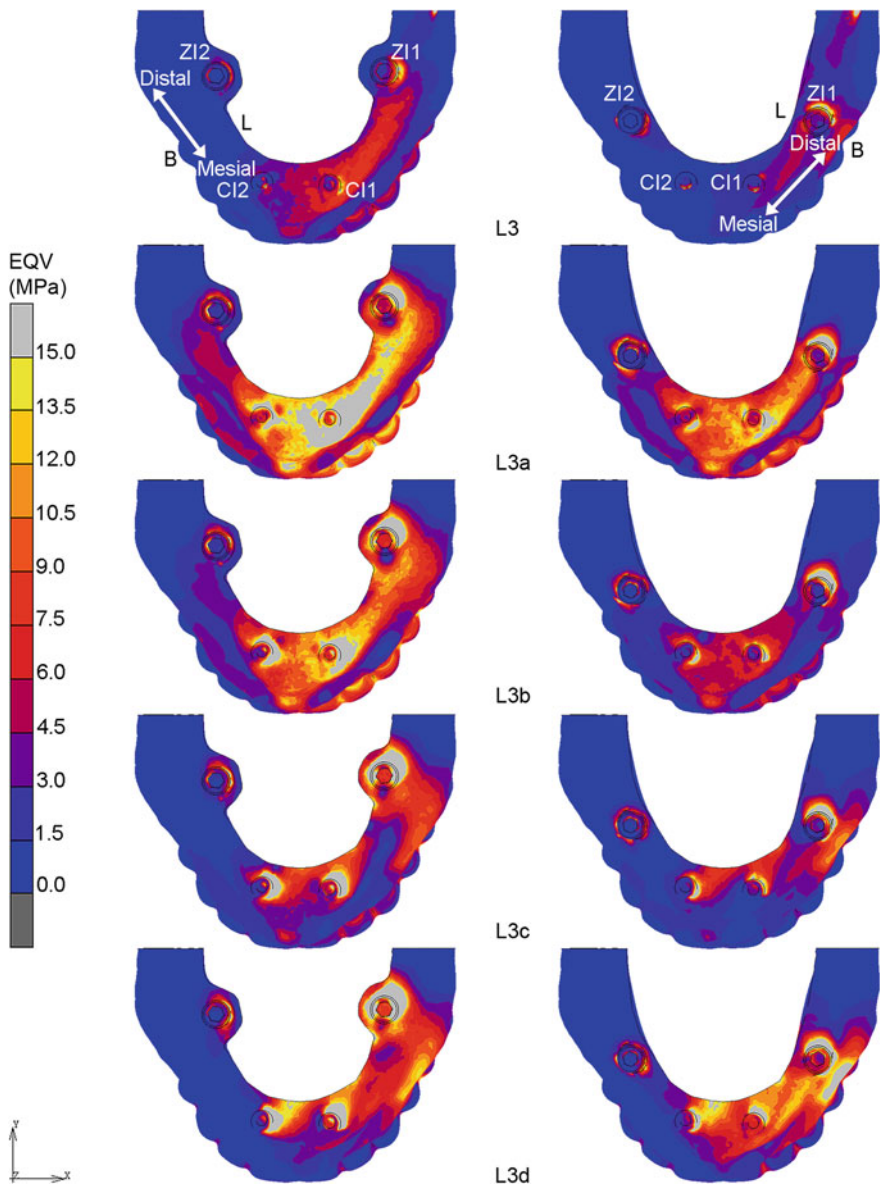


Fig. 6.4 Comparison of EQV distribution within framework under L3 to L3d for the intrasinus and extramaxillary approach (left to right) as viewed from top axial (B = Buccal, L = Lingual)

than extramaxillary approach in ZI1 and ZI2, respectively. As expected, ZI1 model located on the working side possessed a higher stress value than ZI2 (13–76 %). Also, in ZI1 model, the maximum stress that generated under L3a was increased

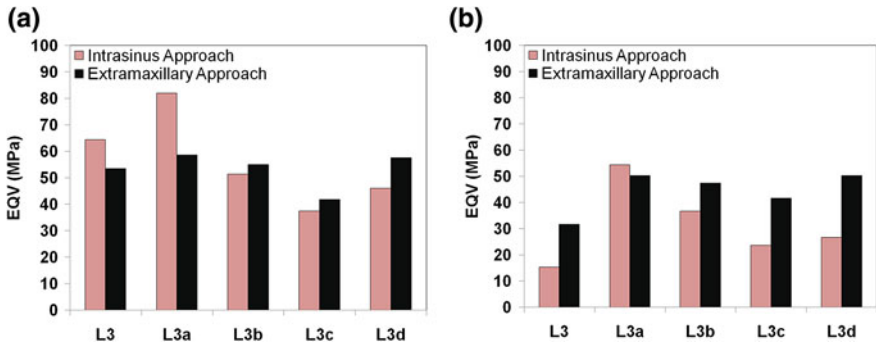


Fig. 6.5 Comparison of EQV magnitude within (a) ZI1 (working side) and (b) ZI2 (non-working side) for both surgical approaches at different load directions

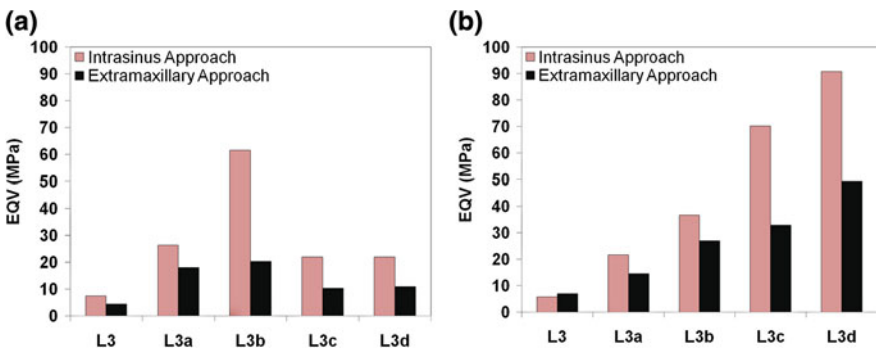


Fig. 6.6 Comparison of EQV magnitude within (a) CI1 (working side) and (b) CI2 (non-working side) for both surgical approaches at different load directions

about 21 and 7 % for intrasinus and extramaxillary approach, respectively, as compared to the vertical load at similar point of load application.

For the conventional implants, intrasinus approach seemed to record higher EQV magnitudes than extramaxillary approach within both CI1 (32–67) and CI2 (26–53 %). A wider stress distribution area was seen at the coronal portion of implant bodies as the load inclination increased (Figs. 6.7, 6.8, 6.9, 6.10).

Although the zygomatic implant head emerged closer to the occlusal load axis in the mesio-distal direction (y-axis) through the intrasinus approach, it did not give a major difference in stress values generated as compared to the extramaxillary approach when loaded by oblique forces except under L3a (the maximum EQV recorded). It seems like the single horizontal force component in the mesio-distal direction and a higher value of vertical force are more predominant in influencing the stress magnitudes in the intrasinus approach. The possible factor that affects a higher maximum stress recorded in that approach is the increase of distance between implant head to the midline of restoration in the bucco-lingual

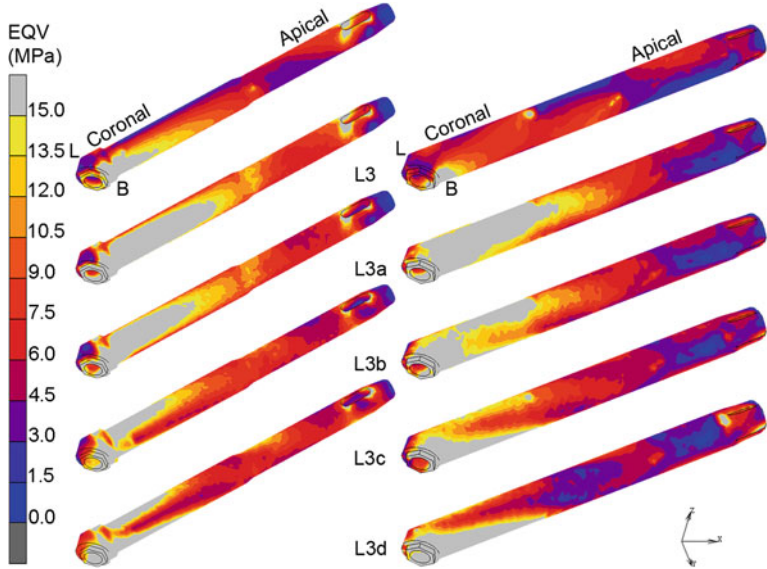


Fig. 6.7 Comparison of EQV distribution within ZI1 under L3 to L3d for the intrasinus and extramaxillary approach (left to right) as viewed from frontal

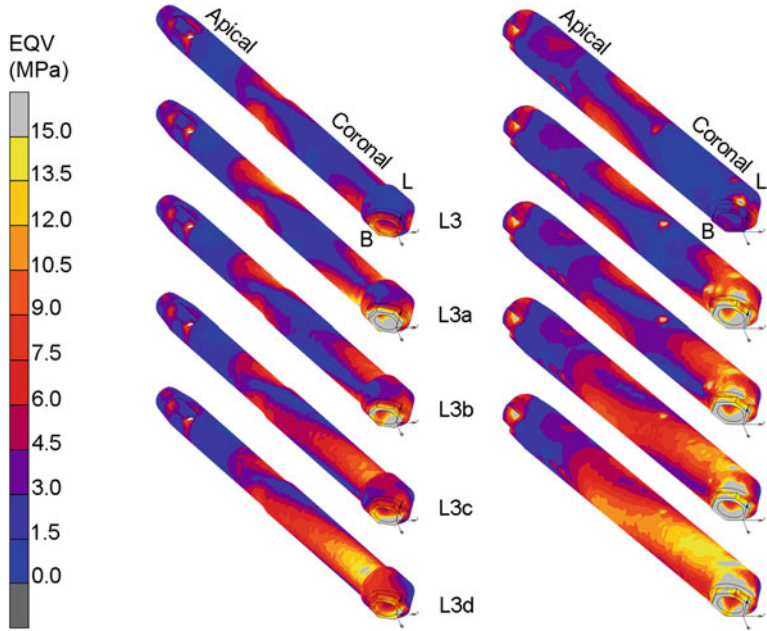


Fig. 6.8 Comparison of EQV distribution within ZI2 under L3 to L3d for the intrasinus and extramaxillary approach (left to right) as viewed from frontal

Fig. 6.9 Comparison of EQV distribution within CI1 under L3 to L3d for the intrasinus and extramaxillary (left to right) as viewed from frontal

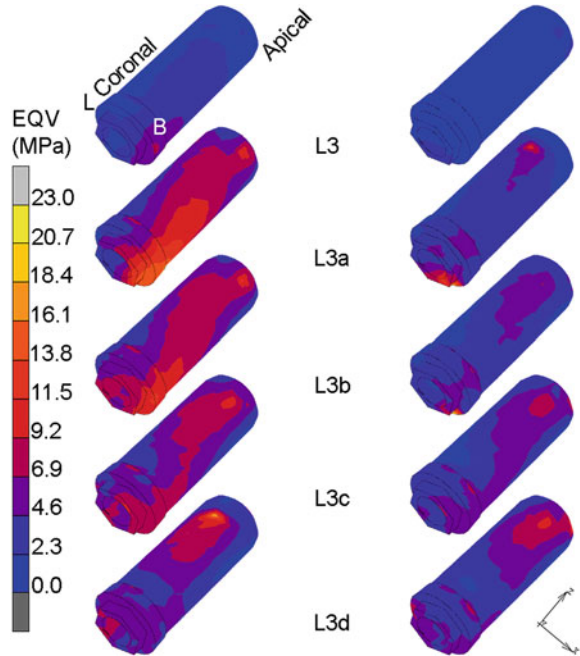
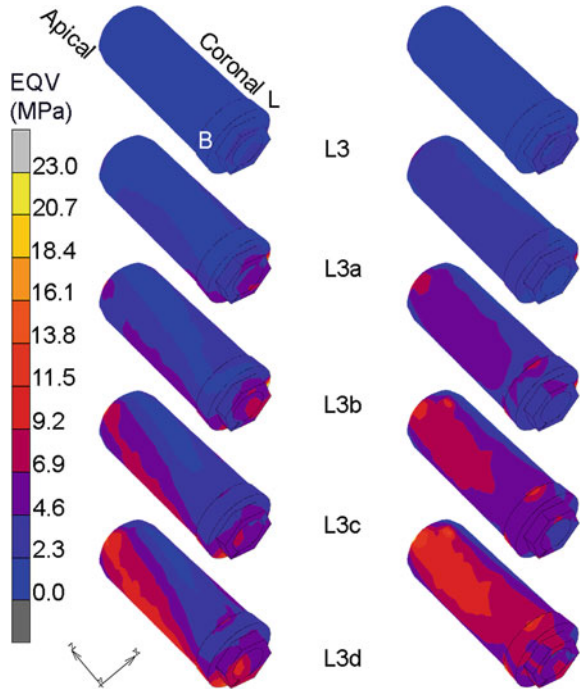


Fig. 6.10 Comparison of EQV distribution within CI2 under L3 to L3d for the intrasinus and extramaxillary approach (left to right) as viewed from frontal



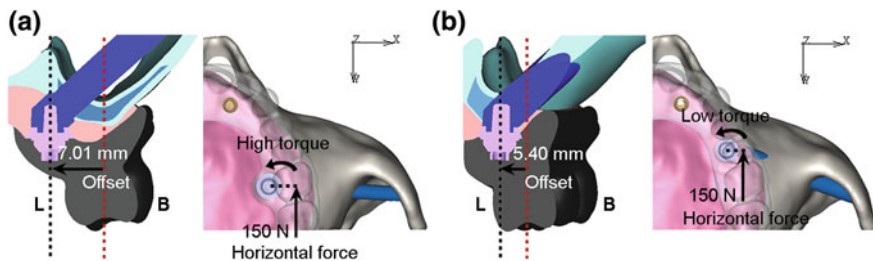


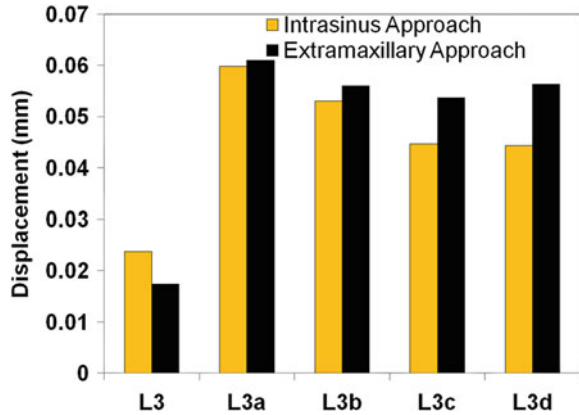
Fig. 6.11 Comparison of horizontal implant offset in the (a) intrasinus and (b) extramaxillary approach model shown in cross-sectional view under L3a

direction towards the palatal region (Fig. 6.11). According to Weinberg, for every 1 mm of horizontal implant offset, the torque magnitude can be increased to average 15 % [22]. In this numerical simulation, the offset was approximately 7.01 and 5.40 mm for the intrasinus and extramaxillary approach, respectively. Thus, it was estimated about 105 of torque increase in the intrasinus compared to the extramaxillary approach, 80 that giving about 24 % differences. The findings of the simulation support the estimation by showing that the maximum stress value within ZI1 in the intrasinus approach was 28 higher than the one in the extramaxillary approach as loaded by oblique force. The stress peaked at the abutment-implant body connection for both approaches due to the strong connection between the two parts. This could be a possible clarification of abutment screw fractures or loosening and implant failures as reported in clinical-based studies [23]. The torque generated from the horizontal components (F_x and F_y) of oblique load mostly influenced the implant body with a higher generated stress.

Although the increase of occlusal loading inclination had increased the magnitude of torque imposed on ZI1, however, it has been noted that the value of vertical load component (F_z) was also reduced consecutively from L3a to L3d (150–106 N) (see Sect. 4.5.4). The values of torque produced were much smaller in the extramaxillary approach compared to the intrasinus since the existence of two horizontal load components in the opposite direction particularly in the bucco-lingual (x -axis) and mesio-distal (y -axis) direction which has cancelled each other in some way progressively. One load might leave a clockwise rotation (lower horizontal load (F_x) magnitude) whilst the other one has a counter clockwise rotation (higher horizontal load (F_y) magnitude) exerted on the implant body. As the cantilever effect is more predominant in the extramaxillary approach, a greater torque cancellation has been achieved and the zygomatic implant bodies being more affected by bending moment from the action of vertical load component. It might be a possible explanation where the approach leaves a discouraging impact on the stress levels recorded in both zygomatic implants while the reverse was seen for the conventional implants under L3b to L3d.

The level of maximum stress generated within all implant bodies in all loading conditions have no tendency to implant failures since titanium alloys are known can

Fig. 6.12 Comparison of maximum displacement magnitude of framework for both approaches at different load directions



tolerate stresses up to 900 MPa [4]. Similar finding was found for the framework model where gold alloy can bear the stresses up to 786 MPa. All the maximum stress values were under the yield strength of the materials used.

6.2 Displacement of Prosthetic Components

Under the application of oblique loads (L3a to L3d), the displacement values of the framework model were nearly two times higher in the intrasinus and three times higher in the extramaxillary approach, as compared to the vertical load (L3) at similar loading point (Fig. 6.12). L3a led to the highest displacement of the framework within all loading inclinations with the maximum values recorded were 0.0598 and 0.0610 mm in the intrasinus and extramaxillary approach, respectively, with only 2 % differences. Furthermore, the framework model appeared to less displace when it was loaded by the oblique forces with the angle higher than 0°. The extramaxillary approach had a higher potential to influence the framework displacement than the intrasinus regardless of the force component inclinations with 2–21 % (Fig. 6.13).

All implant models in both approaches had also demonstrated a higher tendency to displace under oblique loads as compared to vertical load at similar point of load application. From Fig. 6.14a, extramaxillary approach exhibited higher displacement magnitude of ZI1 than intrasinus when the load applied obliquely (6–20 %), however, the reverse outcome was observed under vertical load (39 % lower). In overall, the ZI2, on the other hand, seemed to displace more under the application of both vertical (10 % higher) and oblique loads (23–33 % higher) in extramaxillary approach when compared with intrasinus (Fig. 6.14b). The figures also show the deformation of zygomatic implant bodies. It was clearly showed that the coronal portion of implant body deformed more than the apical portion in both intrasinus and extramaxillary approaches (Figs. 6.15 and 6.16).

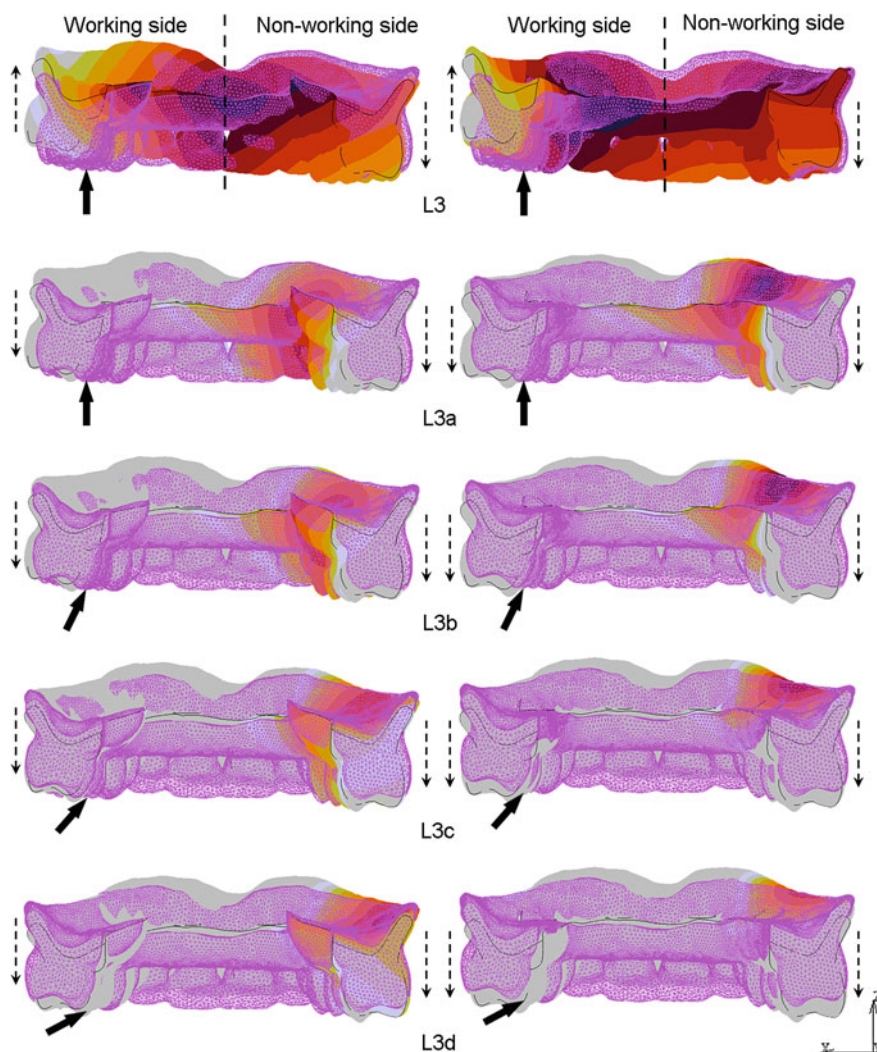


Fig. 6.13 Posterior view of framework motion in the intrasinus and extramaxillary approach (left to right) on L3 to L3d with deformation magnification factor of 100. The largest displacement of framework occurred in the z-axis. In all loading conditions, a tilting of the framework was observed. For L3, the working side of the framework was shifted up whilst the non-working side was lifted down under the action of the loading. Concerning the oblique loads, the reverse rocking motion of framework on the working side was seen and it showed more effective as the loading inclination increased. Generally, intrasinus approach exhibited less rocking motion of the framework than extramaxillary in all loading directions except for L3

The engagement of implant in the cortical layer of zygoma was about 37 and 44 % for intrasinus and extramaxillary approach, respectively, that is significantly higher than in the maxilla, which is around 5 and 25 % for the corresponding

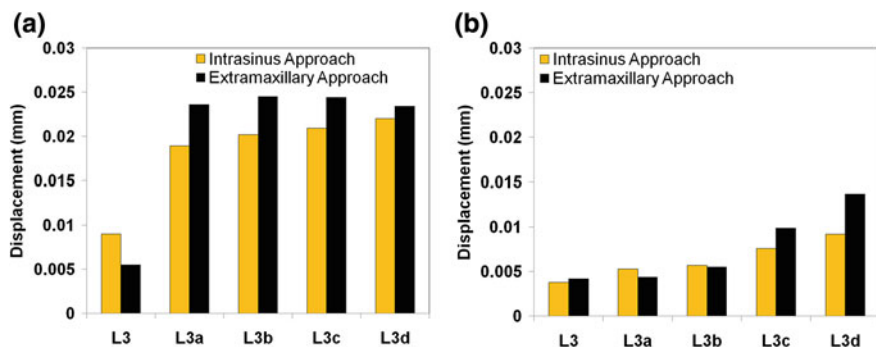


Fig. 6.14 Comparison of maximum displacement magnitude of (a) ZI1 (working side) and (b) ZI2 (non-working side) for both approaches at different load directions

approaches (Fig. 6.17). The implant in the extramaxillary approach was likely to have low displacement value due to high bone-to-implant contact. Nevertheless, the excess bulk of the framework design in the intrasinus approach due to zygomatic implant head emergence has provided more retention to resist the deformation regardless of occlusal loading inclinations, as the coronal implant portion surrounded by the alveolar bone, therefore, reduced the displacement of prosthetic components.

Based on Fig. 6.18a, it could be clearly seen that CI1 in intrasinus approach possessed higher magnitude of displacement than the one in extramaxillary under both types of loading, generally. Dissimilar finding was discovered for the displacement of CI2 where extramaxillary approach showed more significant implant displacement compared to the one in intrasinus with 55 and 5 % higher values under vertical and oblique loads, respectively (Fig. 6.18b). The largest implant displacement concentration region was observed under the oblique load of 45° inclination at the coronal part of the implant body in the bucco-lingual direction for both approaches (Figs. 6.19 and 6.20).

In general, the prosthetic components in the extramaxillary approach have a higher tendency to displace than in the intrasinus approach regardless of the loading location or direction. Despite of having a greater implant-to-bones contact region (56 higher) and longer path of implant penetration in the zygoma (56 % longer), it does not seem to provoke a positively outcome on implant dislocation. It seems possible that these results are owing to the cantilever effects because of the zygomatic implant placement that mainly decrease the implants and framework stability although the application of angled implant in the posterior region of maxilla is known can preserve the implant longevity. However, it is important to know that the path and position of implant anchorage within bones resulting in final prosthesis configuration could also give a major implication on the total stability of prosthetic components.

Based on literature, the value of micromotion between 50 and 150 μm is a major concern as it can put the implant body at risk for potential failure [1].

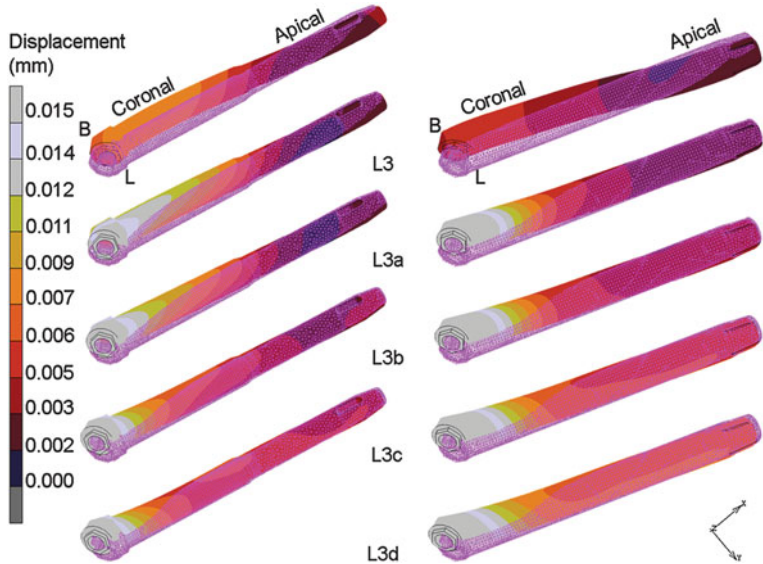


Fig. 6.15 Comparison of displacement pattern of ZI1 under L3 to L3d for the intrasinus and extramaxillary approach (left to right). The original position is shown by pink colour outline

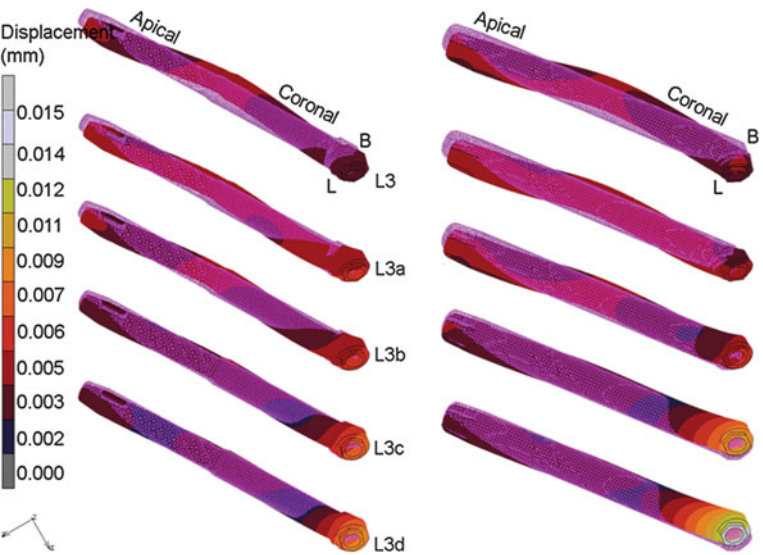


Fig. 6.16 Comparison of displacement pattern of ZI2 under L3 to L3d for the intrasinus and extramaxillary approach (left to right). The original position is shown by pink colour outline

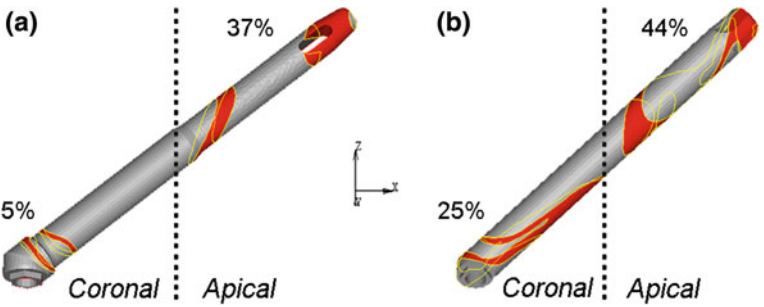


Fig. 6.17 The bone-to-implant contact for the (a) intrasinus and (b) extramaxillary approach

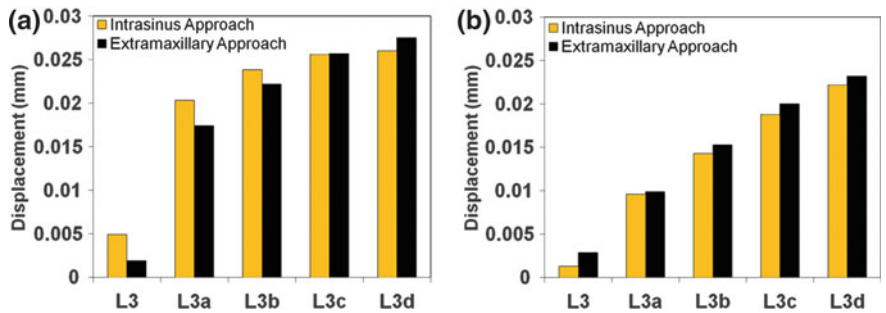


Fig. 6.18 Comparison of maximum displacement magnitude of (a) CI1 (working side) and (b) CI2 (non-working side) for both approaches at different load directions

The maximum value of 61 μm generated by the framework model in the extramaxillary approach under oblique loading was slightly higher than the intrasinus approach (59 μm). However, the percentage of nodal displacement did not cover a large volume that could result in implant failure. Whereas all maximum displacement magnitudes of the zygomatic implant body found in the intrasinus being 22.0 and extramaxillary approach, 24.5 μm are lower than the threshold motion limit reported in the literature.

6.3 Deformation of Zygomatic Implant Body

In general, the body of a zygomatic implant has a high tendency to deform from its coronal part to the middle of implant body, without significantly affecting the apical portion, regardless of the types of surgical approach used. This finding indicates that adequate strength is achievable for anchorage in the zygomatic bone for both approaches, with no critical deformation found in the apical part. The

Fig. 6.19 Comparison of displacement pattern of CI1 under L3 to L3d for the intrasinus and extramaxillary approach (left to right) as viewed from frontal

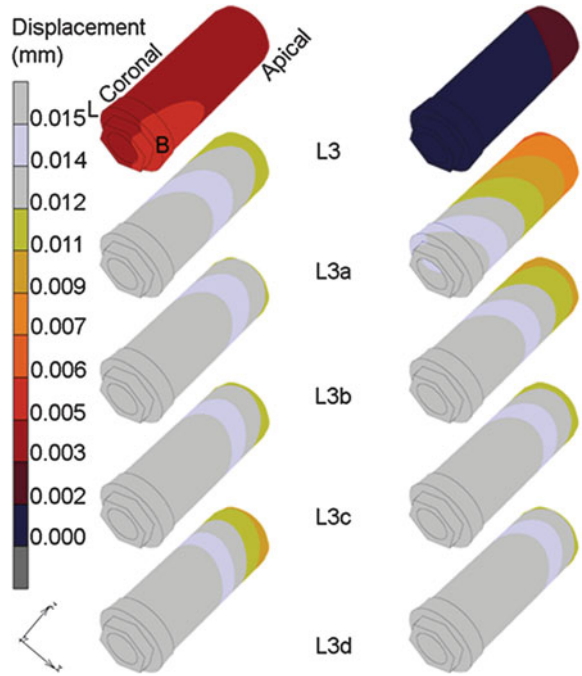
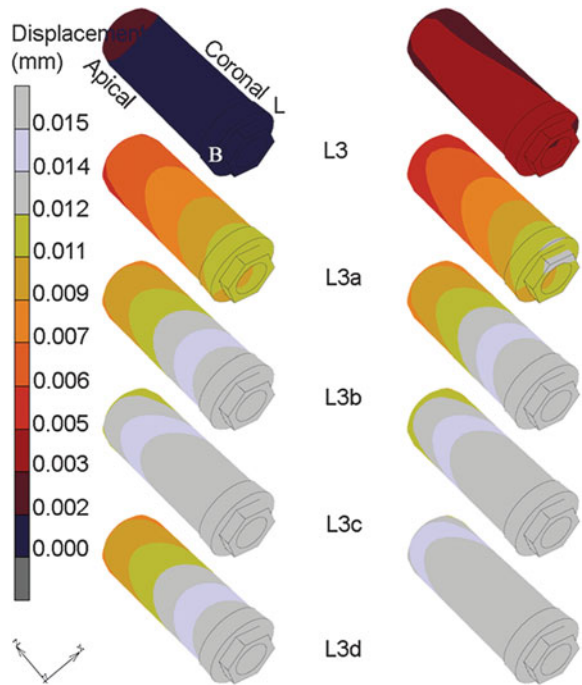


Fig. 6.20 Comparison of displacement pattern of CI2 under L3 to L3d for the intrasinus and extramaxillary approach (left to right) as viewed from frontal



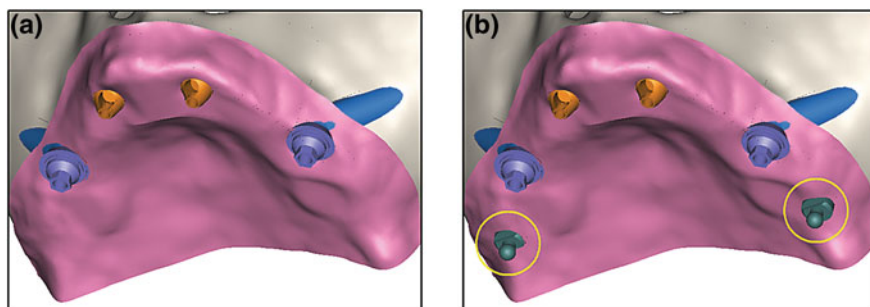


Fig. 6.21 **a.** Original configuration and **(b)** the placement of short implants with ball-type attachment for the extramaxillary approach

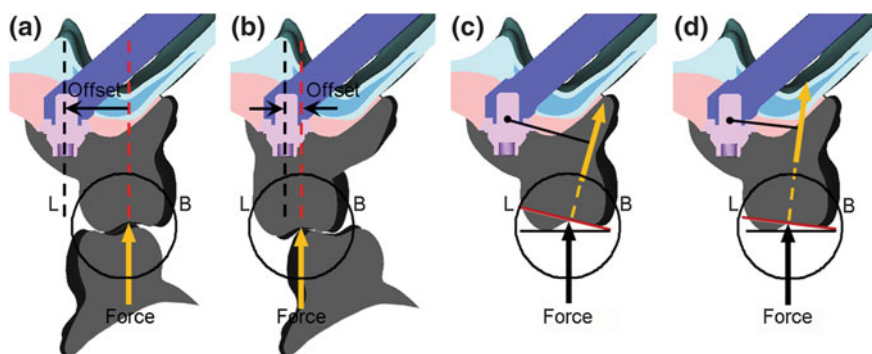


Fig. 6.22 **a.** Normal occlusion. **b** Cross occlusion. **c** Steep cusp and **(d)** Reduced cusp inclination

zygomatic bone has a wider and thicker cancellous bone that can confer initial stability to the implant. However, Nkenke et al. have revealed that the parameters of zygomatic bone are poor for implant placement [24]. Zygomatic implant also tended to be highly bent under horizontal or lateral load due to its increased length to width ratio [16]. The low strength of implant engagement in the residual alveolar bone ridge due to limited bone quantity could be another reason for implant body bending.

It has also been reported that the success of zygomatic implants can be guaranteed by inserting the implants into four cortical portions. This finding is in agreement with the work of Stievenart et al. who described that the success of treatment using zygomatic fixtures mostly depends on the strength of the zygomatic cortical bone [25]. A total of four cortical layers penetration were accomplished in both approaches as observed through the preparation of FEA models in the analysis. The literature reports that the initial stability of the implants could be increased if there is more than one cortical anchorage were achieved [18]. The implants emerge on the zygoma surface at Sect. 6 in both surgical approaches, which is the ideal site for the zygomatic implant insertion according to Rigolizzo et al. [26]. Anchorage within the trabecular bone is less required as the strength of

anchorage in the cortical layer could successfully retain the prosthesis. Depending on the anatomy of the zygoma, the implant body also penetrates through a small volume of cancellous bone. Another important reason for the placement of implant within the zygomatic bone is the fact that the bone has very little tendency towards resorption or regeneration as discussed by Hayashi et al. [27].

6.4 Prosthetic Configuration Improvement

The findings of this text suggest that the cantilever effects as mainly seen in the extramaxillary approach could be reduced by using a support system, such as the IL System as illustrated in Fig. 6.21. This system uses a short implant and a ball-type attachment as an additional retention for distal extension of cantilevered prosthesis [11]. Through a 2D FEA, this system has shown desirable results of stress dispersion within the bone and the implant when compared to conventional cantilevered prostheses. For the intrasinus approach, the effects of horizontal implant offset could be reduced by placing the prosthesis in cross-occlusion. Furthermore, the shallow cusp obtained by reducing cusp inclination can be incorporated into the construction of the prosthesis because it can disperse horizontal load more efficiently, thus, reducing torque-producing forces (Fig. 6.22).

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Summary

To reiterate, this text set out to evaluate the effects of different surgical approaches of zygomatic implants placement on biomechanical behaviours generated within bones and prosthetic components in various occlusal loading locations and directions through 3D FEA. Within the limitations of the analysis, the results of simulated static loadings and non-linear analysis support the following conclusions:

1. In all models tested, the zygomatic implant was revealed to absorb most of the posterior loads while the conventional dental implants in premaxillary region responsible to the anterior load.
2. Apart from that, the pure vertical load was better to be tolerated rather than oblique load even though the vertical load itself left lateral load effects in angled implant application. The oblique load had significantly increased the stress and displacement values within nearly all parts investigated in both surgical approaches.
3. With regards to the action of oblique load, the intrasinus approach exhibited a much higher stress value recorded than the extramaxillary approach within bones, framework and all implants except for zygomatic implant placed in the non-working side.
4. The prosthetic components in the extramaxillary approach had a higher tendency to displace from its original position as compared to the intrasinus approach under simulated masticatory loadings.
5. The zygomatic implant performance in the extramaxillary approach was highly affected by the cantilever effect while for the intrasinus approach, it much more related to the horizontal implant offset due to excess bulk of framework design.
6. It had also been found that the maximum stress verified on nodes of the implant and framework models were smaller than the stress limit or yield strength of respective materials used in both surgical approaches. The zygomatic implants in the extramaxillary approach promoted slightly higher value of maximum

stress recorded than the intrasinus approach, whilst the reverse was seen for the conventional implants.

7. There is less significant discrepancy of average bone stress magnitudes recorded between both approaches. The masticatory loading was primarily transmitted and supported by the zygomatic bone.

Since this is the first ever investigation on comparison of surgical approaches for the placement of zygomatic implants via finite element method, therefore, it needs more time to develop further. It can be concluded that both intrasinus and extramaxillary approaches possess several advantages and disadvantages under all aspects investigated. The intrasinus approach showed more satisfactory and encouraging results under various occlusal loading locations and could still be a viable treatment option, however, it has resulted in more stress increases and deformation within bones and implants to sustain loads in the horizontal direction. The introduction of the latest surgical approach of extramaxillary, on the other hand, could be recommended and being a reasonable treatment option with some improvements made to address the cantilever effects seen in that approach. The most important point for the placement of zygomatic implants in severely atrophic posterior maxillae is the clinical mastery of the techniques, hence determining the success of the treatment.

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